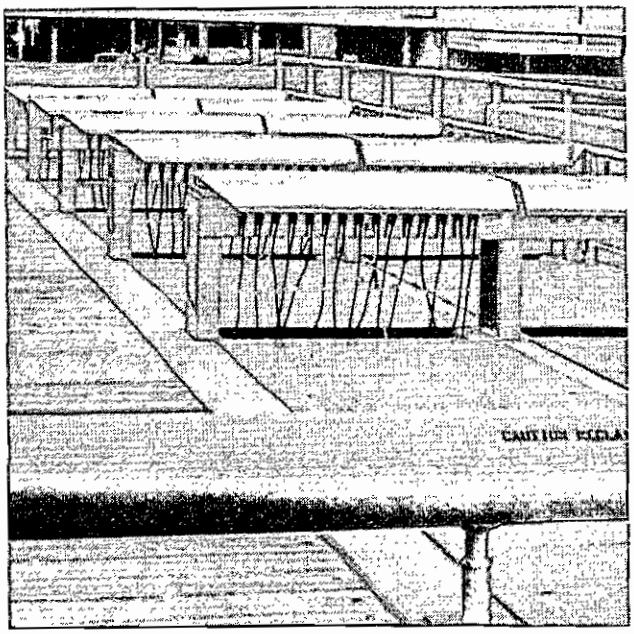

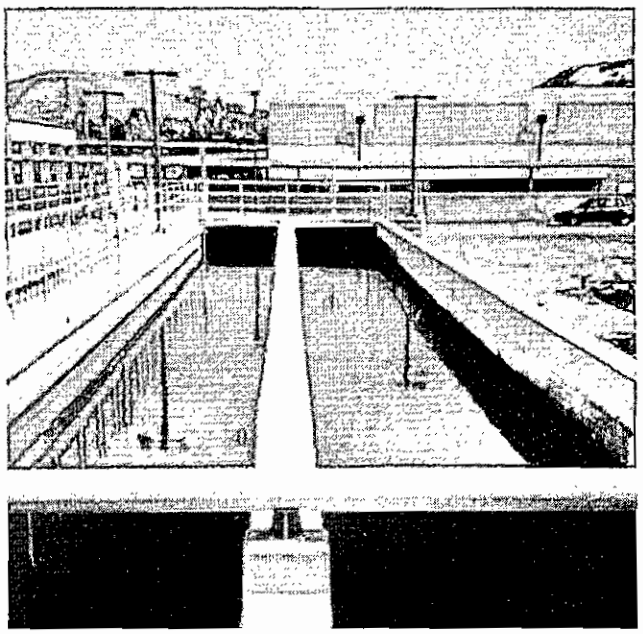

Elsinore Valley Municipal Water District and National Water Research Institute

Final Project Report

A Comparative Study of UV and Chlorine Disinfection for Wastewater Reclamation

April 1994

MONTGOMERY WATSON

MONTGOMERY WATSON

May 18, 1994

Mr. John E. Hoagland
Elsinore Valley Municipal Water District
P.O. Box 3000
31315 Chaney St.
Lake Elsinore, CA 92531-3000

Dear Mr. Hoagland:

Montgomery Watson is pleased to submit this final report on A Comparative Study of UV and Chlorine Disinfection for Wastewater Reclamation. This report is the culmination of a research project jointly funded by the Elsinore Valley Municipal Water District (EVMWD) and the National Water Research Institute (NWRI). The project was designed to demonstrate the safe and effective use of ultraviolet light as a disinfectant alternative to chlorine in meeting the most restrictive wastewater reclamation standards for the State of California.

This project was the first UV light disinfection equivalency study performed at a full-scale tertiary wastewater treatment facility for an extended testing period. The data demonstrate long term system reliability as well as providing a direct measure of full-scale dose requirements for reclamation standards. This study also provided a comprehensive side-by-side comparison of chlorination and UV light disinfection by-products determined utilizing state-of-the-art analytical techniques. The study also evaluated development of a UV lamp fouling curve to use in assessing the lamp cleaning frequency required at the EVMWD facility to achieve a minimum requred UV light inactivation dose.

We have appreciated the opportunity to work with EVMWD during this project and look forward to a continued working relationship.

Sincerely,

Joan A. Oppenheimer

Joan A. Oppenheimer
Principal Investigator

Joseph A. Wojslaw
Vice President

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Table of Contents

MONTGOMERY WATSON

TABLE OF CONTENTS

Table of Contents
(Continued)

Table of Contents
(Continued)

Table of Contents
(Continued)

LIST OF TABLES

LIST OF FIGURES

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Executive Summary

MONTGOMERY WATSON

EXECUTIVE SUMMARY

Reclamation of wastewater necessitates production of an effluent that meets potable water standards whenever human contact may occur. The effectiveness of chlorine as a biocide has been well documented, but recent concerns have arisen over the potential toxicity of chlorination by-products. Use of chlorine is also becoming less attractive due to stringent fire code restrictions, risk management prevention programs, and the safety concerns associated with handling a toxic material. Air toxics monitoring programs, performed at publicly owned treatment plants in response to federal, state, and local government regulations, have also identified chlorination by-products as emitted air pollutants. Finally, utilities in arid regions of the United States frequently fail to meet the concentration limit for total dissolved solids specified in their National Pollutant Discharge Elimination System permit and the addition of chlorine and subsequent dechlorination further exacerbates the problem. All of these factors have contributed to the recent interest in substituting ultraviolet (UV) radiation as the disinfectant of choice for wastewater effluents treated to reclamation standards.

UV light disinfection is being utilized in place of chlorine at secondary wastewater treatment facilities throughout North America. The application of UV light for disinfection of filtered secondary effluent to meet the most stringent California Wastewater Reclamation Criteria (CWRC) of 2.2 total coliform per 100 milliliters was recently demonstrated at three independent pilot studies performed in California. Although these studies provide the basis for the UV dose requirement published in the Guidance Report entitled "UV Disinfection Guidelines for Wastewater Reclamation in California" prepared by the National Water Research Institute for the State of California Department of Health Services in September 1993, the studies have various limitations which do not allow complete demonstration of the equivalency of UV and chlorine disinfection performance. These limitations consist of:

- the uncertainty in extrapolating performance from pilot-scale to full-scale;
- the difficulty in assessing treatment reliability due to the limited duration of the pilot-scale studies;

- the lack of side-by-side chlorination data by which to gage UV performance in terms of microbial inactivation, formation of by-products, and production of whole effluent toxicity;
- the lack of operational data elucidating the impact of lamp fouling on UV dose.

The study reported herein was designed to demonstrate the "equivalency" of UV and chlorine disinfection by simultaneously evaluating performance of both treatment processes at full-scale over an extended period of operation for a nitrified and partially denitrified filtered secondary effluent. The study evaluated the ability of chlorine and UV to consistently achieve adequate reduction of indigenous fecal coliform, indigenous *fecal streptococci*, indigenous *enterococci*, indigenous heterotrophic plate count (HPC), seeded poliovirus, and seeded MS2 bacteriophage at the doses providing total coliform density of $\leq$ 2.2 MPN/100 mL. Bench-scale studies were also performed to determine the predictive value of bench-scale data for full-scale process performance. Formation of disinfection by-products was also monitored through extensive characterization of the organic content of the treated effluent preceding and following UV and chlorine disinfection. The chronic whole effluent toxicity (WET) was also characterized through comparison of WET data obtained for the full-scale treated effluent preceding and following disinfection by UV and chlorine.

This report is based upon work supported by the Elsinore Valley Municipal Water District and by the National Water Research Institute under award number WR-92-04. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the National Water Research Institute.

STUDY BACKGROUND

The Elsinore Valley Regional Wastewater Treatment Plant, located in the City of Lake Elsinore, California was selected as the study site. Liquid treatment at the Regional Plant consists of bar screening, extended aeration via oxidation ditch, secondary clarification, monomedia deep bed anthracite filtration, and chlorination. The plant's second chlorine contactor was retrofit with a UV system (UV 3000, Trojan Technologies Inc. of London, Ontario, Can) consisting of 5 UV banks. Each bank contains 15 modules and 8 lamps per

module for a total of 600 lamps oriented in an axial direction to the effluent flow. Each low pressure mercury discharge lamp has an arc length of 58 inches, and is enclosed in a 0.9 inch diameter quartz sleeve to prevent direct contact with the wastewater effluent. The system was designed to deliver a UV output of 26.7 watts/lamp after 100 hours of lamp operation and an average UV dose greater than 140 mW•sec/sq cm at average daily flow and peak week flow.

The bench-scale inactivation experiments were performed using a 3-L chlorine batch reactor and three Trojan Model 605 Plus flow-through reactors configured in series. Collimated beam experiments were performed with MS2 bacteriophage to obtain a dose-response curve to use as a calibration check of the bench-scale and full-scale UV reactor doses derived from the single point source summation (SPSS) model supplied by the manufacturer. The collimated beam apparatus consisted of 2 inch diameter copper pipe suspended <0.25 inches above a 52 mm petri dish containing 10 mL of the filtered secondary effluent seeded with a pure culture of MS2 bacteriophage. The UV intensity at 254 nm at the water surface was measured with a calibrated radiometer (UVP, San Gabriel, CA).

Five replicate bacterial inactivation experiments were performed at bench-scale. Twenty-one sets of full-scale samples were collected from the UV system and the chlorine contact basin over a 9 month period. Five different UV dose and chlorine dose samples were collected for most of the full-scale experiments. MS2 bacteriophage seedings were performed with 7 of the full-scale experiments to allow for an alternative measure of the UV dose which could be compared with the SPSS calculation method. Vaccine strain polio virus seedings were performed with 5 of the full-scale experiments. To allow for characterization of the upper portion of the inactivation curves, 60% of each UV lamp was covered with an aluminum sleeve to obtain lower UV doses. Ten consecutive days of sampling were conducted with the lamps uncovered to determine the minimum UV dose to meet the most stringent CWRC coliform requirement of ≤2.2 MPN/100 mL.

Investigation of organic transformations during bench-scale UV irradiation and chlorination were made using doses of 2000 mW•sec/sq cm and 10 mg/L of chlorine with a 2-hour contact time. The large UV dose of 2000 mW•sec/sq cm was used to maximize the potential for producing measurable by-products. DBP characterization was performed on two chlorinated effluent samples and three UV irradiated samples. Production of chlorine and UV by-products and whole effluent toxicity were also measured at full-scale.

WATER QUALITY CHARACTERIZATION

Water quality characterization of the filtered secondary effluent was performed with each inactivation experiment. The water quality during the bench-scale and full-scale testing was similar. The UV_{254} transmittance ranged from 70% to 80%, turbidity ranged from 0.3 to 1.2 NTU, TSS ranged from 1.5to <10.0 mg/L, the total number of particles ranged from 746 per mL to 6,170 per mL, TDS ranged from 400 mg/L to 980 mg/L, microbial densities varied by one to two log, and the pH ranged from 7.2 to 7.9 units. The 2-hour chlorine demand was approximately 3 mg/L. The treatment plant provides full nitrification and partial denitrification so the ammonia levels were always expected to be less than 0.1 mg/L throughout the study. The variation in measured turbidity, TSS, and total particle counts were too small to demonstrate any meaningful correlation with the UV_{254} transmittance values or the influent bacterial densities. The lowest UV_{254} transmittance values were measured during the winter (approximately January through March) and the highest values were measured during the summer (approximately June through September). The periods of low and high UV_{254} transmittance values did not show any correlation with the influent bacterial densities.

CHLORINE INACTIVATION OF BACTERIA

Chlorine doses within the range of 1.5 to 5.1 mg/L were effective in reducing the total coliform density to ≤2.2 MPN/100 mL and completely inactivating all the other target organisms with the exception of HPC at bench-scale. At these chlorine doses, the HPC density ranged from 0.6 to 2.9 logs. Two bench-scale chlorine kinetic experiments, were performed to try to define the smallest Ct values to achieve complete inactivation of the target organisms. Inactivation data from these experiments demonstrated a Ct value of ≤ 21 mg/L•min to completely inactivate he total and fecal coliform. At a Ct value of 21 mg/L•min, HPC were still measured at a density of approximately 1.2 logs. Inactivation below detection limit for the HPC was not achieved at a Ct value of 57 mg/L•min derived from kinetic experiments or a Ct value of 150 mg/L•min derived from 2-hour contact time experiments.

At full-scale a total coliform density of ≤2.2 MPN/100 mL was consistently meet at a Ct value of ≤ 46 mg/L•min which was similar to the Ct value observed from the bench-scale kinetic experiments. Whenever the ≤2.2 MPN/100 mL coliform requirement was

TABLE ES-1

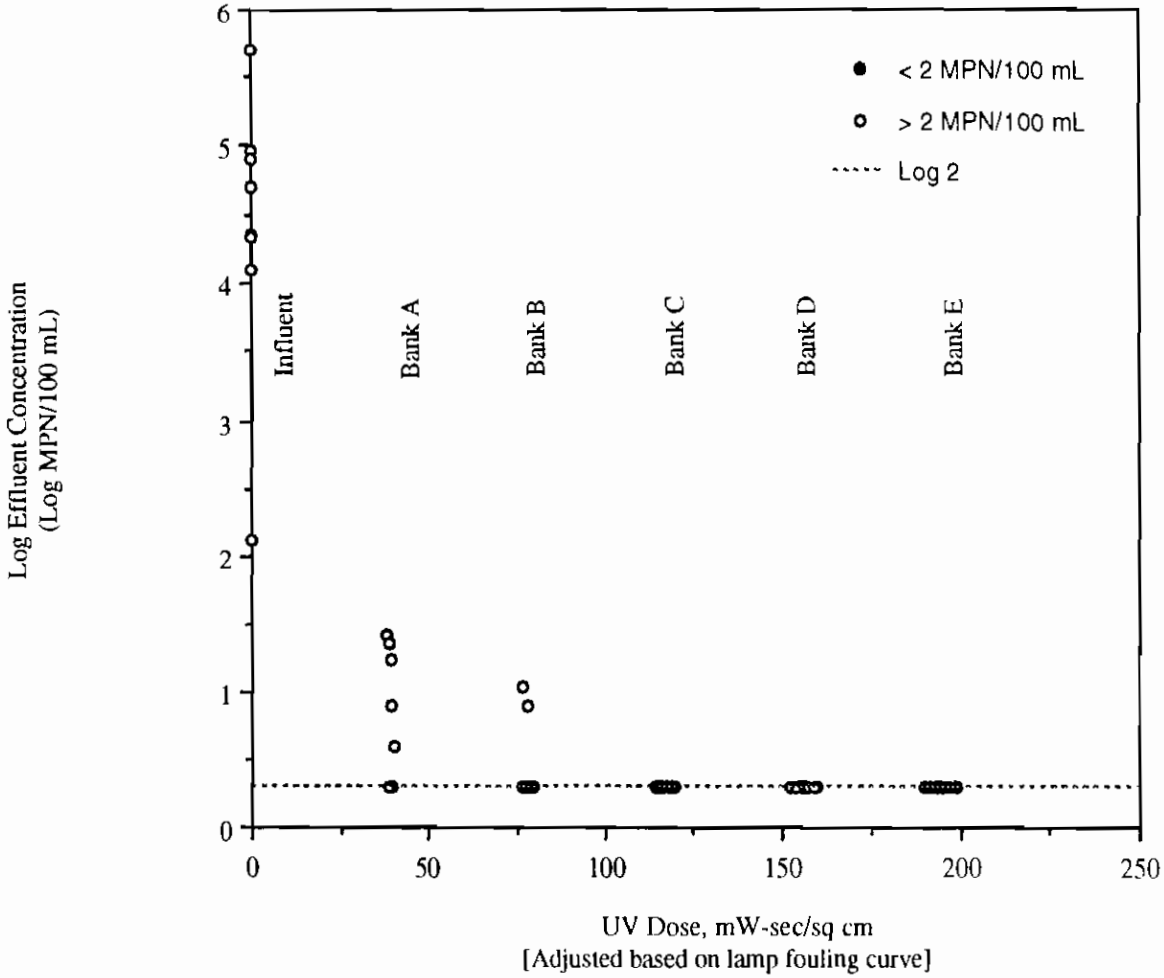
UV DOSE TO ACHIEVE 4 LOG INACTIVATION OF TARGET BACTERIA

Organisms	Bench-scale		Full-scale			
	SPSS dose corrected by MS2 calibration 7 runs		SPSS dose corrected by MS2 calibration 6 runs		SPSS dose corrected by fouling curve 13 runs	
	Mean	Confidence Interval	Mean	Confidence Interval	Mean	Confidence Interval
Total Coliform	53	(36 - 76)	62	(49 - 78)	75	(57 - 99)
Fecal Coliform	35	(30 - 40)	62	(46 - 84)	61	(48 - 78)
Fecal Streptococci *	34	(21 - 56)	54	(32 - 92)	57	(32 - 99)
Enterococci *	38	(19 - 77)	56	(21 - 150)	59	(35 - 99)
Heterotrophic Plate Count	77	(59 - 101)	318	(68 - 1500)	91	(83 - 99)

Notes:

* Dose for 3 log inactivation and only 4 runs conducted

All doses are in mW•sec/sq cm



COMPLIANCE WITH MOST RESTRICTIVE CALIFORNIA TITLE 22 WASTEWATER RECLAMATION REQUIREMENT (≤2.2 MPN/100 mL)

FIGURE ES-3

TABLE ES-2

UV DOSE TO ACHEIVE 4 LOG INACTIVATION OF POLIO VIRUS

Organism	Bench-scale SPSS dose corrected by MS2 calibration 3 runs		Full-scale SPSS dose corrected by fouling curve 5 runs	
	Mean	Confidence Interval	Mean	Confidence Interval
Polio virus	46	(33 - 64)	68	(41 - 113)

All doses are in mW•sec/sq cm

TRACER TESTING OF FULL-SCALE UV REACTOR HYDRAULICS

Maintenance of a minimum UV dose at a full-scale facility is dependent upon continuously maintaining an effective combination of the average reactor UV intensity and exposure time within the UV reactor. Direct measurement of the average reactor UV intensity with UV sensors is not feasible because the sensors are only indicative of the intensity at their specific reactor locations. The sensors are also not an effective on-line method of determining UV intensity at specific locations because they are subject to rapid fouling and component failure which leads to inaccurate readings. At the full-scale installation, the UV intensity sensor readings only returned to approximately 60 percent of their initial readings even after cleaning the lamps and correcting for the intensity loss expected due to lamp aging. Utilizing the fouling curve and the results of the full-scale tracer study demonstrating the adequacy of the theoretical detention time as an estimate of the actual detention time, the lamp cleaning intervals needed to maintain a minimum UV dose at specified peak flow rates and percentage lamp output were calculated.

DISINFECTION BY-PRODUCT CHARACTERIZATION

The filtered secondary effluent, the chlorinated filtered secondary effluent, and the UV irradiated filtered secondary effluent samples were initially analyzed by gas chromatography/mass spectrometry (GC/MS) and liquid chromatography/mass spectrometry (LC/MS) without any preconcentration techniques. No unique peaks were detected in the UV irradiated sample. The chlorinated sample demonstrated production of approximately 75 mg/L of trihalomethanes. Analysis by closed-loop-stripping GC/MS also did not reveal any unique UV by-product peaks.

To maximize the probability of detecting byproducts, a much higher UV dose of 2800 mW•sec/sq cm was applied, the samples were preconcentrated prior to analysis, and a high performance liquid chromatography (HPLC) chromatographic profile was obtained as an initial screening technique prior to performing more detailed mass spectrometry work on isolated chromatographic fractions. Following lyophilization, each sample was redissolved in HPLC-grade water and centrifuged to remove visible particulates. Half of each concentrate was analyzed by direct injection HPLC with UV absorbance at 220 nm and 280 nm. The other half of each concentrate was acidified and extracted with ethyl acetate to

REVERSED-PHASE HPLC OF LYOPHILIZED AND REDISSOLVED FILTERED SECONDARY EFFLUENT DISINFECTED AT BENCH-SCALE (ABSORBANCE AT 220 nm)

FIGURE ES-4

was formed during two separate bench-scale UV irradiation experiments performed more than a month apart, the third factor is not considered as probable as the first two factors.

The unique chlorine peak which occurred at a retention time of approximately 113 minutes on the HPLC screen was also isolated for identification. Low and high resolution FAB-MS analysis was made of the HPLC isolated peak. Upon high resolution mass spectrometry, the isolate was found to consist of two components. One component, representing approximately 60% of the total material, had a measured molecular weight of 463.1195 daltons. The second component, representing approximately 40% of the total material, had a molecular weight of 463.3353 daltons.

Analysis for aldehydes by gas chromatography/electron capture detection (GC/ECD) was also performed. No aldehydes were detected in the filtered secondary effluent and significantly higher amounts of formaldehyde, acetaldehyde, and glyoxyl are formed in the chlorinated sample than the UV irradiated sample. The high levels of aldehydes detected in the chlorinated effluent are in agreement with the findings of a potable water survey sponsored by the United States Environmental Protection Agency's Office of Drinking Water and the Association of Metropolitan Water Agencies in 1988. The survey, performed by the Metropolitan Water District of Southern California and Montgomery Watson, resulted in data suggesting that when a utility's water quality and treatment practices produce a high level of trihalomethanes, they can potentially produce a high level of formaldehyde (Krasner et. al, 1989) .

A summary of detected by-products is presented in Table ES-3. Substitution of UV light for chlorine disinfection eliminated the production of trihalomethanes, significantly reduced the formation of aldehydes, and did not form other regulated organic compounds The one chromatographically resolved unique UV by-product peak produced at bench-scale with a UV dose of 2800 mW•sec/sq cm was not duplicated under full-scale conditions with an applied UV dose of 188 mW•sec/sq cm.

CHRONIC WHOLE EFFLUENT TOXICITY

Samples of the filtered secondary effluent, chlorinated filtered secondary effluent, and UV irradiated filtered secondary effluent obtained from the full-scale plant were analyzed for the following tests:

TABLE ES-3

BY-PRODUCTS IN EVMWD FILTERED SECONDARY EFFLUENT BEFORE AND AFTER DISINFECTION.

Compounds Detected	Filtered Effluent (µg/L)	Chlorinated Effluent (µg/L)	UV Effluent (µg/l)
Chloroform[1]	2.7	21*	2.9†
Dibromochloromethane[1]	0.9	22*	0.8†
Dichlorobromomethane[1]	1.1	27*	1.0†
Bromoform[1]	<0.5	2.7*	<0.5†
1,1,1-Trichloropropanone[2]	Not Detected	0.2§	Not Detected¥
Unresolved scan #1261[2]	Not Detected	0.1§	0.066¥
Unresolved scan #1267[2]	Not Detected	0.096§	0.079¥
Acetaldehyde[3]	<5	21¶	7¶
Formaldehyde[3]	<5	24¶	8¶
Glyoxal[3]	<5	5¶	<5¶
M-Glyoxal[3]	<5	<5¶	<5¶

*Chlorine = 9.8 mg/L dose and 2-hr contact time
†UV = 300 mW•sec/sq cm
§Chlorine = 10 mg/L dose and 2-hr contact time
¥UV = 2800 mw•sec/sq cm
1=Purge and Trap GC/MS (EPA Method 5030/8260)
2=Closed-Loop Stripping GC/MS (Standard Method 6040, 18th ed, 1992)
¶=Samples collected from full-scale reactors (UV dose-188 mW•sec/sq cm)

Seven-day, chronic, fathead minnow (*Pimephales promelas)* static renewal, larval survival and growth test;

Seven-day (three-brood), chronic, *Ceriodaphnia dubia*, static renewal, survival and reproduction test;

Four-day, chronic, *Selenastrum capricornutum,* static, growth test;

The results, summarized in Table ES-4, show no chronic toxicity for the fathead minnow or *Ceriodaphnia* for the undisinfected filtered secondary effluent or the UV irradiated filtered secondary effluent. The No Observable Effect Concentration (NOEC) for survival and growth occurred at 100% effluent concentration resulting in a calculated chronic toxicity value (TUc) of 1.00. Chronic toxicity was observed for the chlorinated filtered secondary effluent for the *Ceriodaphnia* growth bioassay. The reproduction NOEC for the chlorinated sample was 56.00%, resulting in a calculated TUc of 1.79. The *Selanastrum* chronic toxicity tests were inconclusive because of a quality control problem evidenced from the standard toxicant control test. Resampling data indicated chronic toxicity for all three samples with a growth NOEC of 56% and a TUc of 1.79. Therefore, only the chlorination process appears to increase the chronic toxicity of the filtered secondary effluent as evidenced by the increased TUc value for the *Ceriodaphnia* growth bioassay. Increased chronic toxicity of wastewater effluent is frequently found after the chlorination process and it is most typically manifested as an increase in the TUc value for the *Ceriodaphnia dubia* growth bioassay.

COST COMPARISON

Comparison of the total net present value costs of retrofitting the Regional Plant's existing chlorine contactor with a UV system with the costs of upgrading the chlorination system to meet new safety standards and include dechlorination capabilities indicates that the chlorination/dechlorination costs are approximately 8% higher than the UV costs. This difference in the costs is less then the accuracy of the estimates themselves indicating that the cost of the two disinfection processes are comparable when retrofitting an existing faciity. The cost benefit of UV over chlorine disinfection wouldbe much more pronounced for construction of a new facility.

CONCLUSIONS

TABLE ES-4

SUMMARY OF CHRONIC TOXICITY DATA OBTAINED FOR THIS STUDY

Parameter	Filtered Secondary Effluent		Chlorinated Effluent		UV Effluent	
	NOEC	TUc	NOEC	TUc	NOEC	TUc
Fathead Larvae Survival	100%	1.00	100%	1.00	100%	1.00
Fathead Larvae Growth	100%	1.00	100%	1.00	100%	1.00
Ceriodapnia Survival	100%	1.00	100%	1.00	100%	1.00
Ceriodapnia Reproduction	100%	1.00	56%	1.79	100%	1.00
Selanastrum Growth *	56%	1.79	56%	1.79	56%	1.79

Notes:

Based on a single sample collected on November 18, 1993

* *Selanastrum* was repeated with new sample collected on December 14, 1993

UV light disinfection was shown to continuously provide microbial inactivation equivalent to chlorine while reducing the formation of known carcinogenic disinfection by-products and the formation of chronic whole effluent toxicity. This was the first study to demonstrate UV's performance relative to chlorination over an extended timeframe at a full-scale facility treating to meet the most stringent California reclamation standards. Other relevant study findings were:

- the sucessful prediction of full-scale UV inactivation doses from bench-scale data;

- demonstration that the most restrictive total coliform criteria for wastewater reclamation is an appropriate indicator of virus inactivation for UV disinfection;

- generation of a lamp fouling curve which may be a useful site-specific operational tool for scheduling lamp cleaning frequency to insure maintenance of a minimal UV operating dose.

Section 1

MONTGOMERY WATSON

SECTION 1

INTRODUCTION

Reclamation of wastewater necessitates production of an effluent that meets potable water standards whenever human contact may occur. The effectiveness of chlorine as a biocide has been well documented, but recent concerns have arisen over the potential toxicity of chlorination by-products. Use of chlorine is also becoming less attractive due to stringent fire code restrictions, risk management prevention programs, and the safety concerns associated with handling a toxic material. Air toxics monitoring programs, performed at publicly owned treatment plants in response to federal, state, and local government regulations, have also identifed chlorination by-products as emitted air pollutants. Finally, utilities in arid regions of the United States frequently fail to meet the concentration limit for total dissolved solids specified in their National Pollutant Discharge Elimination System permit and the addition of chlorine and subsequent dechlorination further exacerbates the problem. All of these factors have contributed to the recent interest in substituting ultraviolet (UV) radiation as the disinfectant of choice for wastewater effluents treated to reclamation standards.

UV light disinfection is being utilized in place of chlorine at secondary wastewater treatment facilities throughout North America. The application of UV light for disinfection of filtered secondary effluent to meet the most stringent California Wastewater Reclamation Criteria (CWRC) of 2.2 total coliform per 100 milliliters was recently demonstrated at three independent pilot studies performed in California. Although these studies provide the basis for the UV dose requirement published in the Guidance Report entitled "UV Disinfection Guidelines for Wastewater Reclamation in California" released by the State of California Department of Health Services in September 1993, the studies have various limitations which do not allow complete demonstration of the equivalency of UV and chlorine disinfection performance. These limitations consist of:

- the uncertainty in extrapolating performance from pilot-scale to full-scale;
- the difficulty in assessing treatment reliability due to the limited duration of the pilot-scale studies;

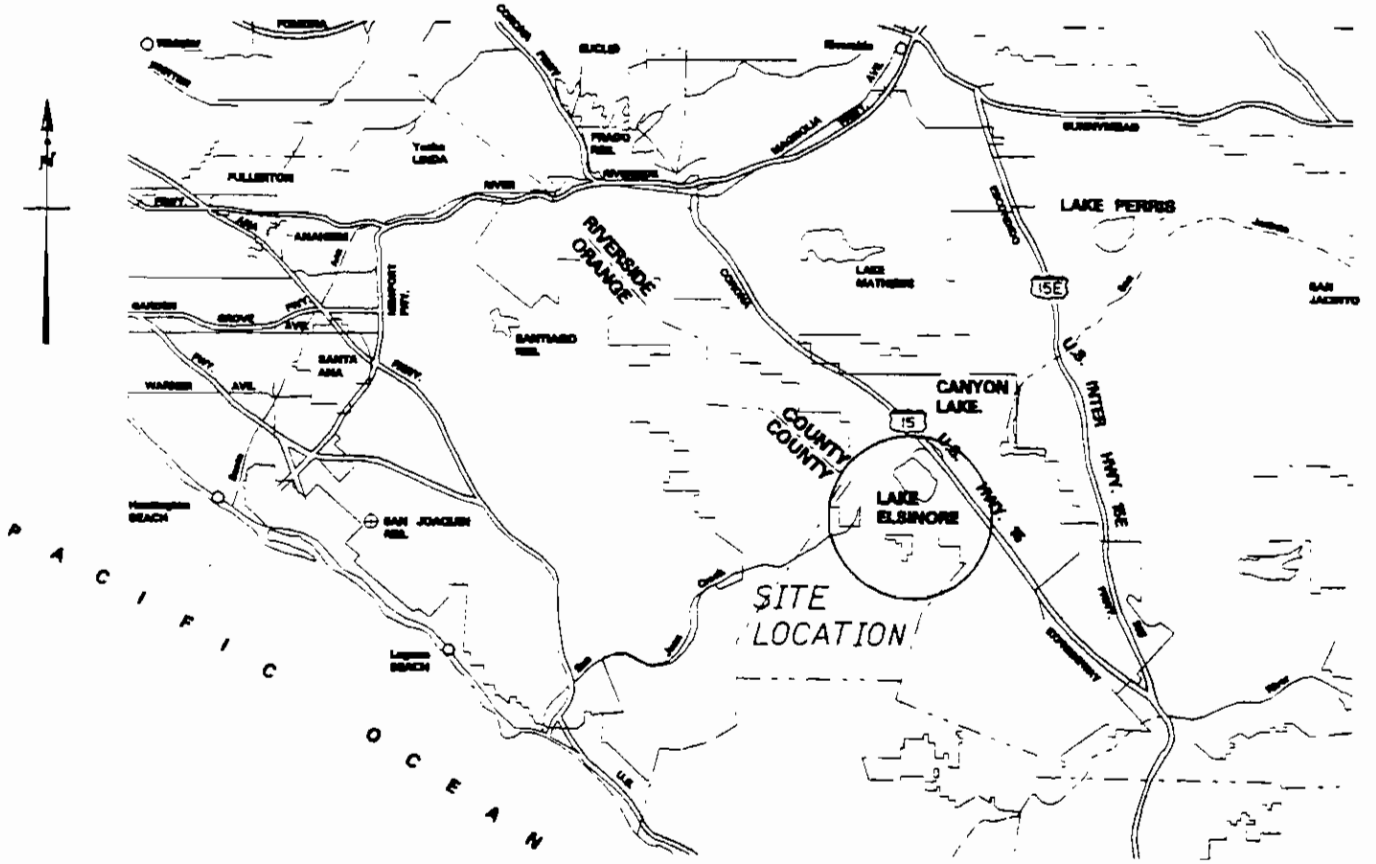
- the lack of side-by-side chlorination data by which to gage UV performance in terms of microbial inactivation, formation of by-products, and production of whole effluent toxicity;
- the lack of operational data elucidating the impact of lamp fouling on UV dose.

The study reported herein was designed to demonstrate the "equivalency" of UV and chlorine disinfection by simultaneously evaluating performance of both treatment processes at full-scale over an extended period of operation for a nitrified and partially denitrified filtered secondary effluent. The study evaluated the ability of chlorine and UV to consistently achieve adequate reduction of indigenous fecal coliform, indigenous *fecal streptococci*, indigenous *enterococci*, indigenous heterotrophic plate count, seeded poliovirus, and seeded MS2 bacteriophage at the doses providing a total coliform density ≤2.2 MPN/100 mL. Bench-scale studies were also performed to determine the predictive value of bench-scale data for full-scale process performance. Formation of disinfection by-products was also monitored through extensive characterization of the organic content of the treated effluent preceding and following UV and chlorine disinfection. The chronic whole effluent toxicity (WET) was also characterized through comparison of WET data obtained for the full-scale treated effluent preceding and following disinfection by UV and chlorine.

STUDY BACKGROUND

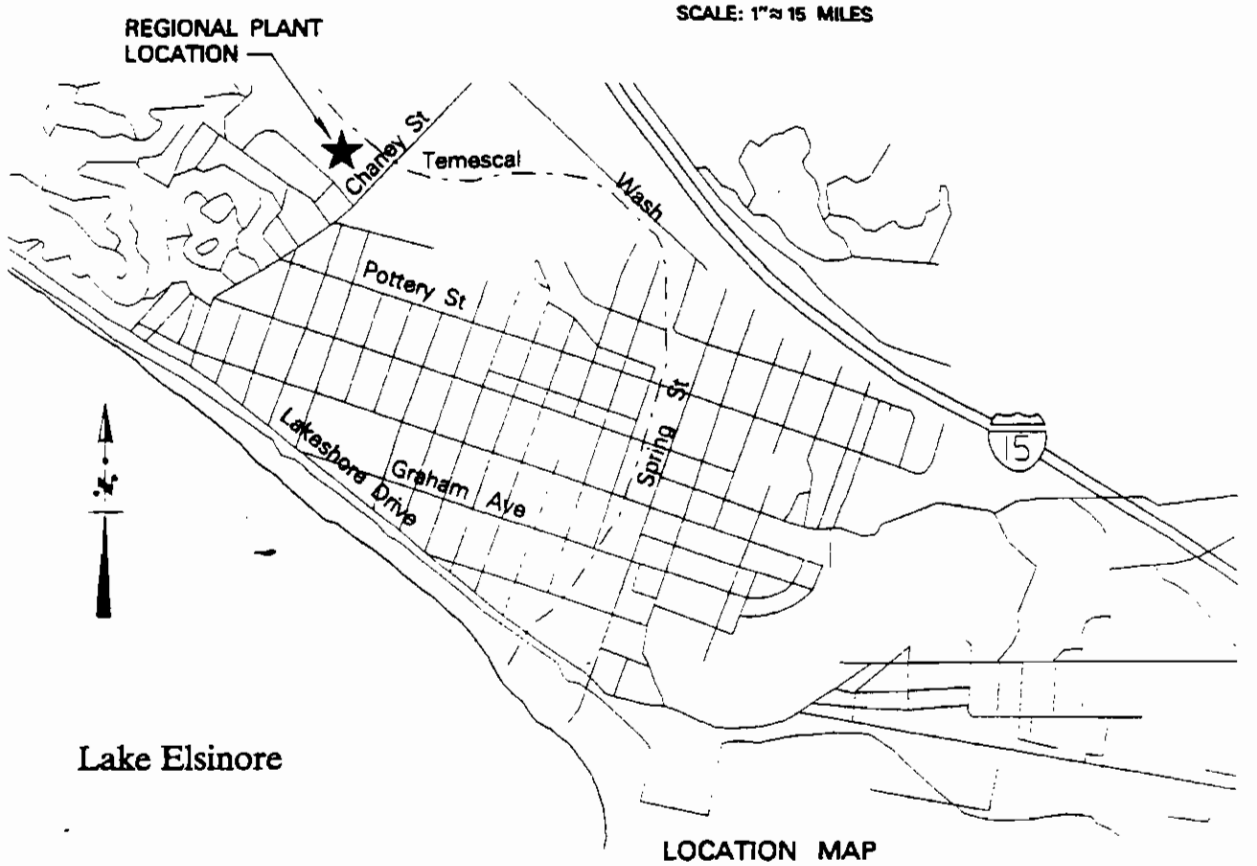
The site selected for this study was the Elsinore Valley Regional Wastewater Treatment Plant, located in the City of Lake Elsinore, California. Elsinore Valley Municipal Water District (EVMWD) owns and operates three advanced wastewater treatment facilities servicing communities within Riverside County and the Regional Plant is the largest facility with an average flow rate of 3 million gallons per day (mgd). The location of this facility is shown in Figure 1-1.

Liquid treatment at the Regional Plant consists of bar screening, extended aeration, secondary clarification, monomedia deep bed anthracite filtration, and chlorination. Gaseous chlorine addition followed by a 2 hour detention time is employed prior to discharge to Temescal Creek. Twenty-five miles from the point of discharge, Temescal Creek joins the Santa Ana River.



VICINITY MAP

SCALE: 1"≈ 15 MILES



LOCATION MAP

SCALE: 1"≈ 2000'

MONTGOMERY WATSON Pasadena, California	ELSINORE VALLEY MUNICIPAL WATER DISTRICT REGIONAL PLANT LOCATION	FIGURE 1-1

The current waste discharge requirements specified for the Regional Plant in the National Pollutant Discharge Elimination System (NPDES) permit are derived from the water quality objectives established for Temescal Creek and the Santa Ana River in a Water Quality Control Plan adopted by the Regional Board on May 13, 1983. Water contact recreation is listed as a beneficial use for both bodies of water. For this reason, disinfection must fulfill the most restrictive requirements set forth in the California Wastewater Reclamation Criteria (Title 22, Division 4, Chapter 3 of the California Code of Regulations). Wastewater disinfection, under this criteria, is considered adequate if the median number of total coliform organisms does not exceed 2.2/100 mL for 7 consecutive days of sampling and the number of total coliform organisms does not exceed 23/100 mL in more than one sample within any 30-day period.

The District is meeting the California Wastewater Reclamation Criteria (CWRC) with the addition of approximately 10 mg/L of gaseous chlorine at the inlet channel of the chlorine contactor. However, effective July 1, 1993, the permit also requires a 30-day average total chlorine residual concentration limit of 0.1 mg/L. Although the District has been able to meet this requirement with their current chlorination practices, installation of dechlorination facilities would be necessary to insure reliable compliance with this limit in the future.

Due to the fact that Temescal Creek flows into the Santa Ana River, the NPDES permit also requires mineral limits which can meet the water quality objectives for the Santa Ana River. The objectives established for the Santa Ana River are more restrictive than those for Temescal Creek resulting in more conservative mineral limits in the permit. The 4-month average total filterable residue concentration limit specified in the permit is 700 mg/L. During certain periods of the year, the TDS concentration of the chlorinated wastewater effluent is close to the permit limit. The current addition of salts to effect chlorination and the future addition of salts for dechlorination will make it increasingly difficult for the District to consistently meet their TDS permit requirement.

A number of other factors detract from the use of chlorine for disinfection. If gaseous chlorine (and gaseous sulfur dioxide for dechlorination) is employed, the risk of handling and use must be considered. In this regard, stringent fire code restrictions and mandatory risk management prevention program development requirements apply. Also, off-gassing of chlorinated compounds from liquid-air interfaces within the treatment facilities has been reported by many studies within the State of California to represent a significant proportion

Section 2

MONTGOMERY WATSON

SECTION 2

LITERATURE REVIEW

INTRODUCTION

This section provides an overview of ultraviolet (UV) disinfection technology as applied to the irradiation of wastewaters with emphasis on secondary and tertiary effluents and discharge standards applicable in California. Specifically, this literature review addresses the following issues:

- Virus and bacteria inactivation comparison for UV irradiation and chlorination.
- The effect of suspended solids and turbidity on the performance of UV disinfection.
- Potential reactions of UV irradiation with organic material and the resulting formation of UV disinfection by-products.
- The extent of photoreactivation of microorganisms and related effectiveness of UV irradiation for disinfection of treatment plant effluents.
- The long-term process reliability associated with elevated suspended solids and UV lamp fouling.
- The life expectancy of UV lamps under field conditions, including the effect of lamp switching frequency.
- The relationship between UV transmittance and color.
- Potential seasonal changes in UV disinfection efficiency.
- Control and measurement of UV dose in full-scale facilities.
- The extent of full-scale use of UV irradiation for waste water disinfection, including water reclamation applications.

(RMPP, 1989). This risk can be classified as having a very low probability of occurrence (based on the historical evidence) but having potentially serious consequences when accidents do occur.

- The use of hypochlorite is often offered as a safe and equally effective alternative to chlorine gas. From the perspective of public safety, however, the use of hypochlorite as a replacement for chlorine may not provide the decreased level of liability exposure that is intended. Commercial hypochlorite is almost always produced from chlorine gas (White, 1986). This means that the risk of shipping, receiving, storing, and handling liquid chlorine gas is simply relocated from the point of use (the treatment plant) to the producer's site (hypochlorite production facility). This is referred to as the "hazard relocation phenomenon". On-site generation of hypochlorite from salt brines may be an alternative solution for large wastewater treatment plants from the perspective of public safety but the process is very labor-intensive (White, 1986; EES, 1990).

UV Irradiation. Due, in part, to the problems associated with chlorination, substantial attention has been given to the design and testing of UV irradiation for the disinfection of wastewaters. UV irradiation is an emerging technology which may offer distinct benefits as compared with chlorination:

- No known deleterious disinfection by-products are formed during UV irradiation (Wolfe, 1990).

- No undesirable chemical residual remains after disinfection which would otherwise need to be removed due to potential toxic effects on the receiving water body (Wolfe, 1990).

- The need for handling and storage of hazardous chemicals such as chlorine gas and sulfur dioxide is eliminated.

- UV irradiation systems are characterized by the simplicity of operation as compared with chlorination and other alternative disinfection technologies. This relative simplicity results from the insensitivity of UV disinfection to several changing water quality parameters, e.g., pH, temperature, concentration of ammonia, amines nitrite, and hydrogen sulfide (Scheible and Bassell, 1981).

- UV disinfection is becoming economically competitive with chlorination due to continuous advances in lamp technology (Whitby *et al.*, 1991).

Due to the benefits outlined above, the use of UV irradiation in wastewater treatment has steadily increased. Currently, there are about 700 operating UV disinfection wastewater plants in North America (Cairns, 1991). The following discussion addresses the significant parameters and phenomena that affect the performance of UV irradiation for the disinfection of wastewaters.

FACTORS AFFECTING DISINFECTION EFFICIENCY

This section describes the mechanisms of chlorine and UV disinfection and discusses how these mechanisms affect the inactivation efficiency of bacteria and viruses. The relative efficiency of UV inactivation of these organisms is quantified and compared to chlorine. Further, important wastewater quality parameters that affect UV disinfection are discussed. The effect of UV irradiation on organic compounds contained in wastewater and the issue of potential UV disinfection by-products are reviewed next. Finally, the phenomenon of microorganism photoreactivation following UV disinfection and its impact on required UV doses are discussed.

Mechanism of Chlorine Disinfection

Chlorine reacts rapidly with various organic compounds of bacterial cells, causing ultrastructural and physiological alterations. Chlorination results in disruption of growth, metabolism and reproduction of the cells (Haas, 1980; Haas and Engelbrecht, 1980). If ammonia is present in the wastewater, the predominant form of disinfectant will be monochloramine. This chlorine species reacts primarily with sulfur containing compounds (Jacangelo and Olivieri, 1985; Jacangelo *et al.*, 1987a). For some bacteria, a multiple-hit mechanism may be necessary before the organism is inactivated (Jacangelo *et al.*, 1991).

Mechanism of UV Disinfection

The biocidal properties of UV light under laboratory conditions have been known since the late 1800's (Downes and Blunt, 1877). UV light in the wavelength range 240 to 260 nm kills microorganisms by causing photochemical damage to RNA and DNA (Jagger, 1967).

When UV energy is absorbed by the genetic material of microorganisms, pyrimidine dimers are formed which join neighboring cytosine or thymine moieties by a cyclobutane ring. These dimers are the major cause of the lethal effects of UV radiation. The pyrimidine dimers prevent deoxyribonucleic acid from replicating, which results in the death of the cell (WPCF, 1984). The pyrimidine bases of viral RNA consist of uracil and cytosine instead of thymine and cytosine as in bacterial DNA. Thus, less readily induced uracil dimerization, and not thymine dimerization, may be the primary mode of UV inactivation of viruses (Harris *et al.*, 1987b).

When injured organisms are exposed to light energy at wavelengths between 310 and 500 nm, fission of the pyrimidine dimers occurs, the original base sequence is restored, and the organisms can then replicate normally (WPCF, 1984). This phenomenon is called photoreactivation; its extent and conditions are discussed further in a later section of this review.

Inactivation of Bacteria and Viruses by Chlorination and UV Irradiation

The inactivation of bacteria and viruses by UV irradiation and chlorination has been the subject of several reviews. The efficacy of free and combined chlorine against bacteria and viruses was reviewed by Safe Drinking Water Committee (1980). An excellent research paper on the effects of various forms of free chlorine on the destruction of viruses and bacteria was published by Scarpino *et al.* (1974). The mechanisms of inactivation of microorganisms by chloramines was discussed in detail by Jacangelo *et al.* (1987b). The removal and inactivation of bacteria and viruses by chlorination, UV disinfection and other treatment processes was reviewed by Leong (1983) and, more recently, by Sobsey (1989). A review of bacteriophages as model viruses in water quality control was discussed in detail for chemical disinfectants and UV irradiation in a recent review article (IAWPRC, 1991).

Inactivation of Bacteria and Viruses by Chlorination. The disinfecting ability of chlorine and chlorine compounds in the treatment of water and wastewater has been known for many years. Chlorine speciation, water quality parameters, and microorganism type affect the inactivation to a great extent. Hypochlorous acid (HOCl) ionizes to form hypochlorite ion (OCl^-) and hydrogen ion. The dissociation of hypochlorous acid is dependent chiefly upon pH and, to a much lesser extent, temperature, with almost 100 percent HOCl present at pH 5, and almost 100 percent OCl^- present at pH 10 (Scarpino *et*

al., 1974). HOCl and OCl^- react readily with ammonia in aqueous solution to form inorganic chloramines. Chlorine reacts also with various nitrogen compounds to form organic chloramines; these compounds have little or no biocidal activity (Jacangelo *et al.*, 1987b). The bactericidal efficiencies of the various chlorine species in decreasing order are: hypochlorous acid > hypochlorite ion > dichloramine > monochloramine. For viral inactivation, the efficiencies of monochloramine and dichloramine are reversed (Jacangelo *et al.*, 1987b). Hypochlorous acid is very effective in inactivating many health-related bacteria, such as *E. coli*, *Salmonella* spp., *Shigella* spp., *Legionella* spp. (Sobsey, 1989).

Reoviruses, adenoviruses and echoviruses have been shown to be much less resistant to chlorine disinfection than polioviruses and especially coxsackieviruses (Engelbrecht *et al.*, 1978). This is illustrated by the data presented by the Safe Drinking Water Committee (1980). Coxsackie virus was 50 times and poliovirus 1 was 6.7 times as resistant to inactivation by hypochlorous acid than *E. coli*. Resistance to chlorine disinfection varies also for different types of the same virus. Engelbrecht *et al.*(1978) reported that coxsackie B5 was 40 times more resistant to chlorine than coxsackie A9. Rotaviruses, hepatitis A are generally more resistant to free chlorine than most enteric bacteria, and their resistance to inactivation is even greater in feces and wastewater (Sobsey, 1989).

Inactivation of Bacteria and Viruses by UV Irradiation. Reported relative effectiveness of UV light for inactivation of bacteria and viruses varies depending on the literature source cited. Yip and Konasewich (1972) presented data suggesting that the sensitivity of *E. coli* to UV irradiation is comparable to that of selected viruses including poliovirus, coxsackie virus, adenovirus and influenza. However, studies conducted by Huff *et al.* (1965), Wolf *et al.* (1978), Rice and Hoff (1981), Severin *et al.* (1983) Chang *et al.* (1985) and Dizer *et al.* (1993) suggest that viruses are significantly more resistant to UV radiation than coliforms. Harris *et al.* (1987b) determined that poliovirus and reovirus required approximately 6 and 10 times the dose of *E. coli*, respectively, and approximately 3 and 6 times the dose of *S. faecalis*, respectively for 3 log inactivation (without considering photoreactivation of bacteria). When considering photoreactivation of bacteria, the UV dose required for 3 log bacteria inactivation approximately doubled.

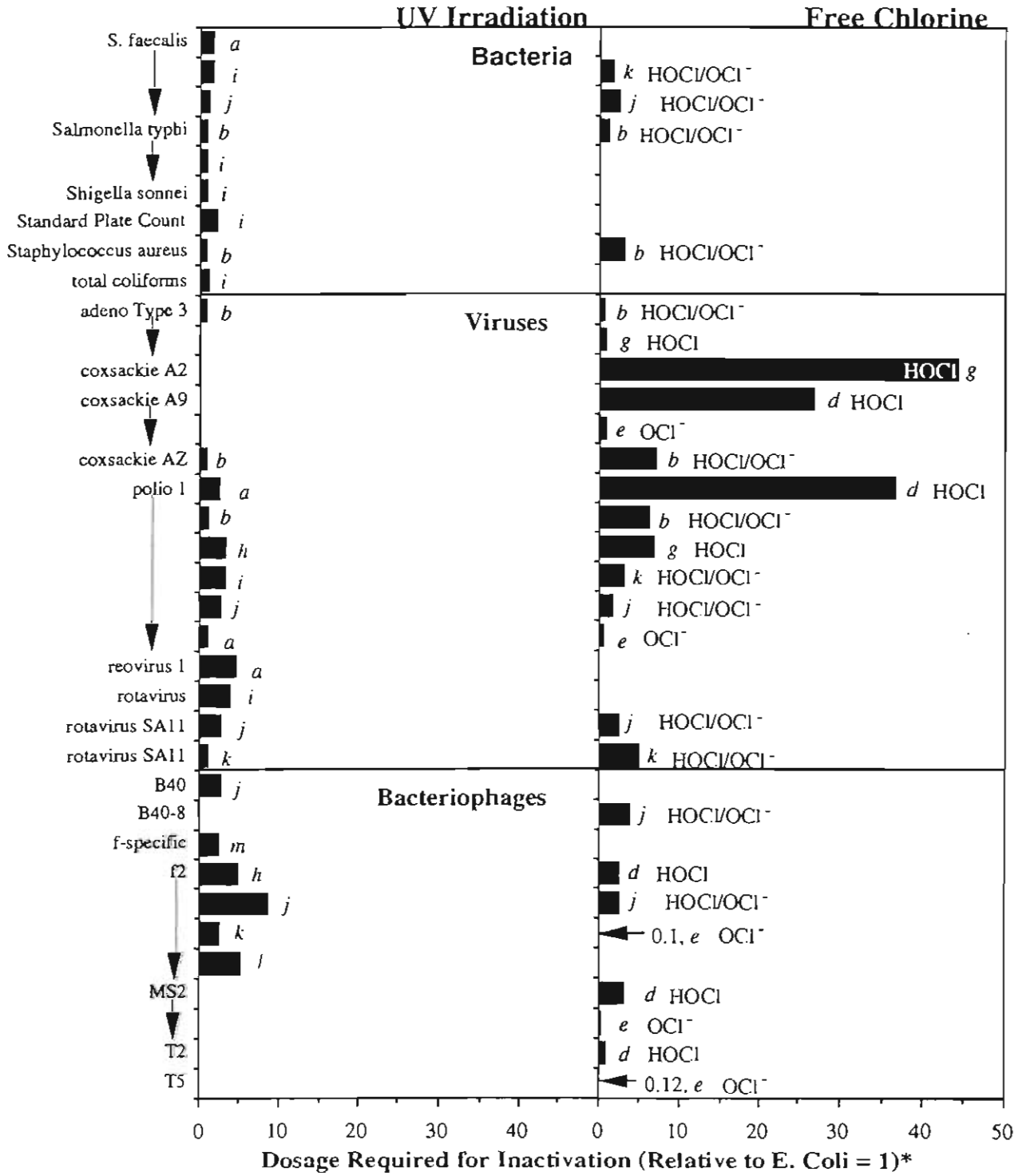
The resistance of bacterial spores and cysts to UV disinfection is a well established phenomenon (Rice and Hoff, 1981; Chang *et al.*, 1985). For example, Chang *et al.* (1985) determined that the UV dose required for 3 log inactivation of *Bacillus subtilis* spores and *Acanthamoeba castellanii* cysts was 2 and 3 times, respectively, greater than the dose

required for similar inactivation of rotavirus. The cysts were considerably more resistant to UV disinfection than various groups of enteric bacteria (*E. coli*, *Streptococcus faecalis*).

The reported resistance of enteric viruses to UV disinfection varied from 0.96 to 1.43 times that of poliovirus 1, with coxsackie and reoviruses being most resistant (IAWPRC, 1991). This difference in resistance of viruses may be attributed to the fact that reovirus is a double-stranded RNA virus whereas poliovirus is a single-stranded RNA virus. Reovirus is also approximately three times larger than poliovirus and has a double protein coat, while poliovirus has a single protein coat (Harris *et al.*, 1987b).

Chlorination versus UV Irradiation for Inactivation of Bacteria and Viruses. The UV disinfection process has been demonstrated to be effective, and in certain cases more effective (particularly in the case of viruses) than either chlorine or ozone (WPCF, 1986). The difference in microorganism sensitivity between chlorination and UV irradiation results from different underlying mechanism of disinfection. UV disinfection involves photo-induced transformation of nucleic acids. The characteristics of the bacterial wall have minimal impact on UV light absorption, except for some bacterial spores equipped with a unique UV light-absorbing protective exterior. By comparison, disinfection with chlorine involves penetration of the active species through the cell wall to reach various cellular components.

Because UV irradiation is a physical disinfection process and chlorination is a chemical one, it is very difficult to directly compare the two in regards to inactivation efficiency. Since the units of dose are different, one cannot compare logs of inactivation of a particular microorganism as a function of concentration and/or time. Consequently, it is necessary to use a common reference organism as a basis from which to compare the two disinfection processes. For this review, *E. coli* was chosen as the reference organism since this microorganism is part of the total coliform group, which serves as the basis for the NPDES permit. Using this concept, Figure 2-1 presents the comparative inactivation of UV irradiation and chlorination. Various studies, which simultaneously compared the inactivation of *E. coli* and other selected microorganisms by UV and chlorine were identified. For the chlorine data, the dosage required for a specified log inactivation of *E. coli* over a certain contact time was determined and assigned the value of 1. Next, the chlorine dosage required for the same log inactivation for the organism to be compared to *E. coli* was determined (the same contact time used). The relative dosages were then compared for the two organisms. For example, if a chlorine dose of 2 mg/L was required



* Based on 2 or 3 log inactivation, depending on study cited (If doses were not varied, then inactivation times were compared).

Note: 1) Italicized letters next to bars represent literature references.

2) Chlorine species next to bars based on pH at which study was conducted.

3) How to read Figure: The larger the bars, the greater the dose needed to inactivate the microorganism relative to *E. Coli*. For example, Coxsackie AZ virus requires approximately 7 times the dose of chlorine needed for the same level of inactivation of *E. Coli*. UV irradiation requires approximately 2 times the dose to inactivate this virus relative to a similar level of inactivation of *E. Coli*.

DISINFECTION RESISTANCE OF BACTERIA AND VIRUSES RELATIVE TO *E. Coli* FOR UV IRRADIATION AND FREE CHLORINE

FIGURE 2-1

for 99% inactivation of *E. coli* after 1 minute, and under the same conditions a chlorine dose of 10 mg/L was required for 99% inactivation of poliovirus 1, then the dosage for poliovirus inactivation relative to *E. coli* was assigned a value of 5. A similar approach was used for UV irradiation. Because pH impacts the species of chlorine present (and thus disinfection efficiency), the primary chlorine species comprising the total chlorine residual were selected for each study. They are presented next to the bars on the graph. All other conditions under which the studies were conducted are shown in Table 2-1.

Since most of the studies were conducted by different researchers under various conditions, only general trends should be discerned from the data. The larger the bar on the graph, the larger the dosage required relative to a similar inactivation of *E. coli*. For example, inactivation of coxsackie AZ virus requires approximately 40 times the dose of free chlorine as compared to a similar inactivation of *E. coli*. The data show that enteric viruses are, in general, as sensitive or more sensitive to UV irradiation than to free chlorine (UV bars are generally the same size or smaller than the free chlorine bars).

In non-nitrified secondary effluent chloramines are the primary component of the total chlorine residual. The data in Figure 2-2 clearly show that for poliovirus 1 and f2 bacteriophage, UV is a more efficient disinfectant than chloramines relative to *E. coli* (bars are smaller for UV irradiation in all cases).

Bacteriophages as Viral Indicators for UV Irradiation. The agents involved in waterborne viral disease are presently difficult to detect in water and wastewater. For monitoring purposes, a model organism would be useful for viruses in the same way as coliform bacteria are used as a model organism for bacterial enteric pathogens (IAWPRC, 1991).

Bacteriophage T3 was found to be relatively sensitive to UV disinfection, whereas f2 was more resistant than any of the animal viruses studied (see Figure 2-1 and 2-2). It appears that only F-specific RNA phages would have a resistance high enough to be an acceptable indicator. F-specific RNA phages hold great promise as indicators for both UV and chemical disinfection processes, especially for pilot- and field-scale studies (Kamiko and Ohgaki, 1989; IAWPRC, 1991). Bosh *et al.* (1989) recommended using a bacteriophage B40-8 as an indicator microorganism because of its high resistance to chlorination and UV disinfection. Phage B40-8 was more resistant to chlorination than polio and rotavirus SA11, and it was as resistant to UV disinfection as the above two viruses. Karst *et al.*

TABLE 2-1

EXPERIMENTAL CONDITIONS AND REFERENCES FOR FIGURES 1 AND 2

(a) Harris, *et al.* (1987b).
Based on UV dose required for 3 log inactivation with photoreactivation.
Bench tests in phosphate buffer; 2 hrs photoreactivation.

(b) Yip and Konasewich (1972).
Based on UV and chlorine doses; log inactivation not reported
Compilation from various sources. No experimental conditions listed.

(c) Shah and McCamish (1972).
Based on time required for 2 log inactivation at 4 mg/L combined chlorine residual.
Bench tests in water at room temperature.

(d) Scarpino, *et al.* (1974).
Based on free chlorine dose (HOCl) for 2 log inactivation after 100 seconds.
Phosphate buffer at pH=6 and 5°C.

(e) Scarpino, *et al.* (1974).
Based on free chlorine dose (OCl^-) for 2 log inactivation after 100 seconds.
Borate buffer at pH=10 and 5°C.

(f) Safe Drinking Water Committee (1980).
Based on dichloramine dose for 2 log inactivation after 60 minutes.
Phthalate buffer at pH=4.5 and 15°C.

(g) Safe Drinking Water Committee (1980).
Based on free chlorine dose (HOCl) for 2 log inactivation after 7 minutes.
Various sources, pH not specified, 0-6°C.

(h) Petrasek, *et al.* (1980).
Based on UV dose required for 2 log inactivation as compared with fecal coliforms.
Pilot scale experiments in secondary effluent.

(i) Chang, *et al.* (1985).
Based on UV dose required for 3 log inactivation.
Bench scale experiments.

(j) Bosh, *et al.* (1989).
Based on time required for 2 log inactivation by 2-3 mg/L free chlorine or UV light.
Tap water, pH=7.7 at 22°C.

(k) Bosh, *et al.* (1989).
Based on time required for 2 log inactivation by 20-24 mg/L free chlorine or UV.
Autoclaved sewage bench test, pH=7.7 at 22°C.

(l) Severin, *et al.* (1983).
Based on UV dose required for 3 log inactivation.
Pure culture experiments.

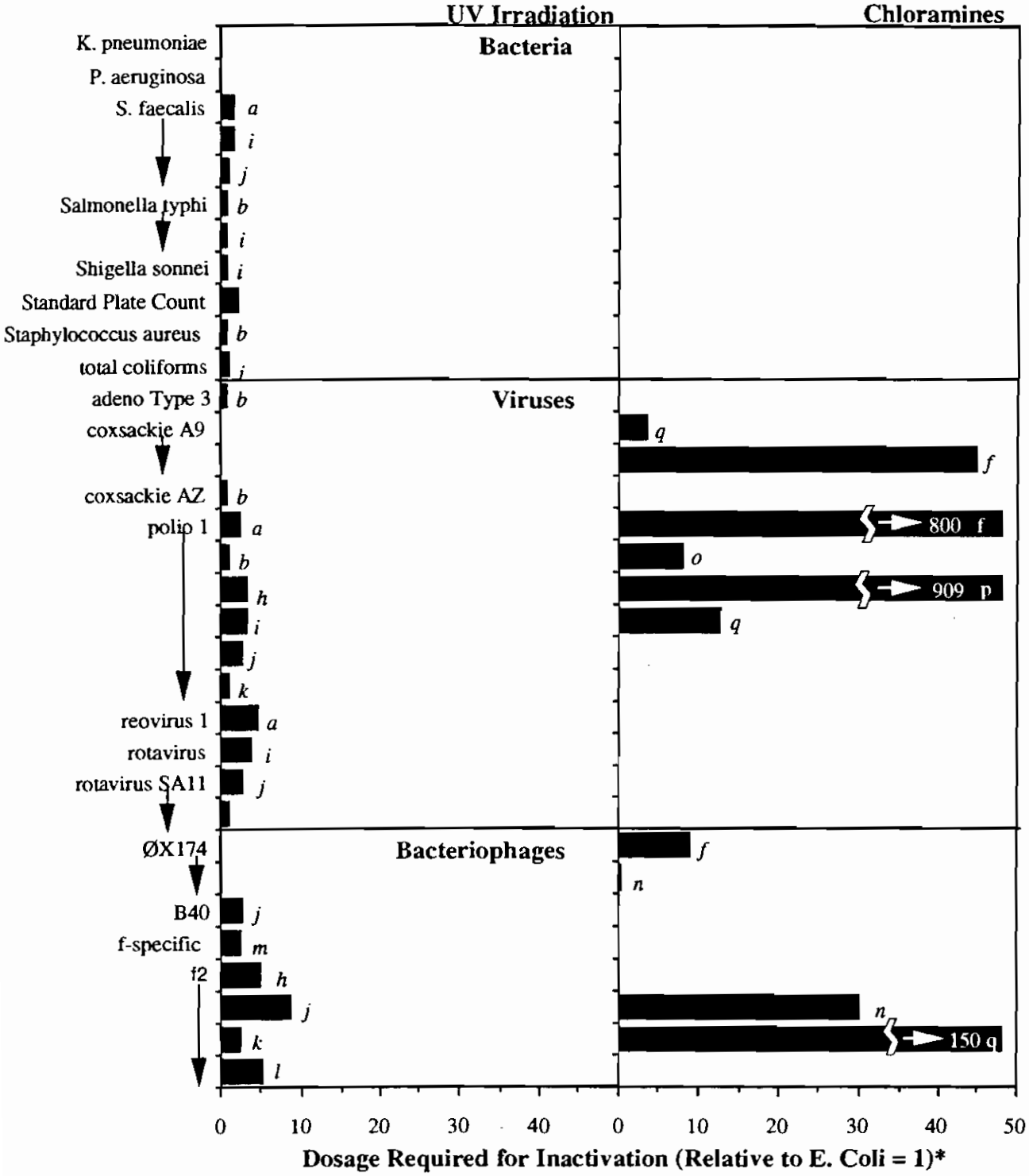
(m) Havelaar, *et al.* (1987).
Based on UV dose required for 3 log inactivation.
Indigenous organisms in secondary effluent.

(n) Jacangelo, *et al.* (1987b).
Based on time required for 2 log inactivation by 10 mg/L monochloramine.
pH=7.0 at 20°C.

(o) Safe Drinking Water Committee (1980)
Based on CT ratio for coli and Polio 1, monochloramine, pH=9.0 at 25°C.

(p) Safe Drinking Water Committee (1980)
Based on CT ratio for coli and Polio 1, dichloramine, pH=4.5 at 15°C.

(q) Dorn (1974)
Based on dose for 2 log inactivation by monochloramine
pH=9.0 at 15°C



* Based on 2 or 3 log inactivation, depending on study cited (If doses were not varied, then inactivation times were compared).

Note: 1) Italicized letters next to bars represent literature references.
2) Figure is read in a manner similar to Figure 1.

DISINFECTION RESISTANCE OF BACTERIA AND VIRUSES RELATIVE TO *E. Coli* FOR UV IRRADIATION AND CHLORAMINES

FIGURE 2- 2

(1991) reported variance in phage recovery rate depending on the water quality and the phage type, and cautioned against indiscriminate use of the coliphages as indicator or index organisms for any application. Instead, the use of phages for only strictly defined systems was recommended.

Wiedenmann *et al.* (1993) reported that the UV dose necessary for a reduction of the MS2 phage by 4 log units was about three times higher than that necessary for hepatitis A virus. Havelaar *et al.* (1990) recommended using F-specific RNA bacteriophage MS2 as a viral indicator for UV irradiation due to the following reasons:

- MS2 is a single-strand RNA virus and consequently its dose-response curve for UV inactivation follows first-order kinetics,
- the structure and size of MS2 are similar to that of the human enteroviruses,
- MS2 has a relatively high UV resistance, comparable to that of bacterial spores,
- MS2 is not pathogenic to humans and thus can be tested without additional safety measures,
- the organism is easily cultivable in titres up to 10^{12} pfu/mL.

Direct comparison between F-specific bacteriophages naturally occurring in tested secondary effluent and the reovirus was reported by Nieuwstad *et al.* (1991). The inactivation rates obtained for indigenous F-specific bacteriophage and the reovirus were very similar. Based on that observation, the authors recommended F-specific bacteriophages as model organisms for UV virus inactivation in secondary effluent. Laboratory propagated F-specific bacteriophage MS2 was inactivated by UV disinfection at a rate which was almost twice that of naturally occurring F-specific bacteriophages, indicating the necessity of designing reactors for practical applications based on field data rather than laboratory experiments (Havelaar *et al.*, 1991).

Wastewater Quality Parameters Affecting UV Disinfection Efficiency

Several variables have been found to affect the disinfection capabilities of UV light for wastewater. Similar to chlorination, the principal variables are the dose of disinfecting agent and wastewater characteristics. There is a need for expanding the understanding of the effect of wastewater quality parameters on UV disinfection. To date, the use of percent transmittance (%T) and, to a lesser extent, the concentration of suspended solids (SS) have been the predominant parameters used.

UV Dose. UV dose is defined as a product of UV light intensity, I, (mW/cm^2) and contact (exposure) time, t, (s):

$$\text{Dose} = I \times t \qquad (mW\text{-}s/cm^2)$$

A lack of standardization in measurement of intensity has made the direct comparison of the results from different studies difficult. Average intensity probes measure the UV light from a single location and, therefore, it is difficult to determine the average intensity within a UV reactor unless numerous intensity measurements are taken. Unlike chlorination, UV disinfection does not provide measurable chemical residual which makes the immediate control of the process difficult. In a full-scale UV disinfection system, the intensity patterns are complex and the average intensity cannot be directly measured with a detector (Qualls *et al.* 1989). The following methods of intensity measurement are reported in the literature: chemical actinometry (Harris *et al.*, 1987c; Johnson and Qualls, 1985; Severin *et al.*, 1984; Severin, 1980), biological assays (Qualls *et al.*, 1989; Qualls and Johnson, 1983; Johnson and Qualls, 1985), and direct calculation (Qualls and Johnson, 1985; Qualls and Johnson, 1983; Scheible, 1987; Scheible *et al.*, 1986; Scheible and Bassell, 1981; Petrasek *et al.*, 1980). A detailed description of the methods for UV dose measurement has been presented in the "Design Manual: Municipal Wastewater Disinfection" (EPA, 1986). The UV dose required varies from system to system depending on water quality, initial coliform density, and reactor geometry.

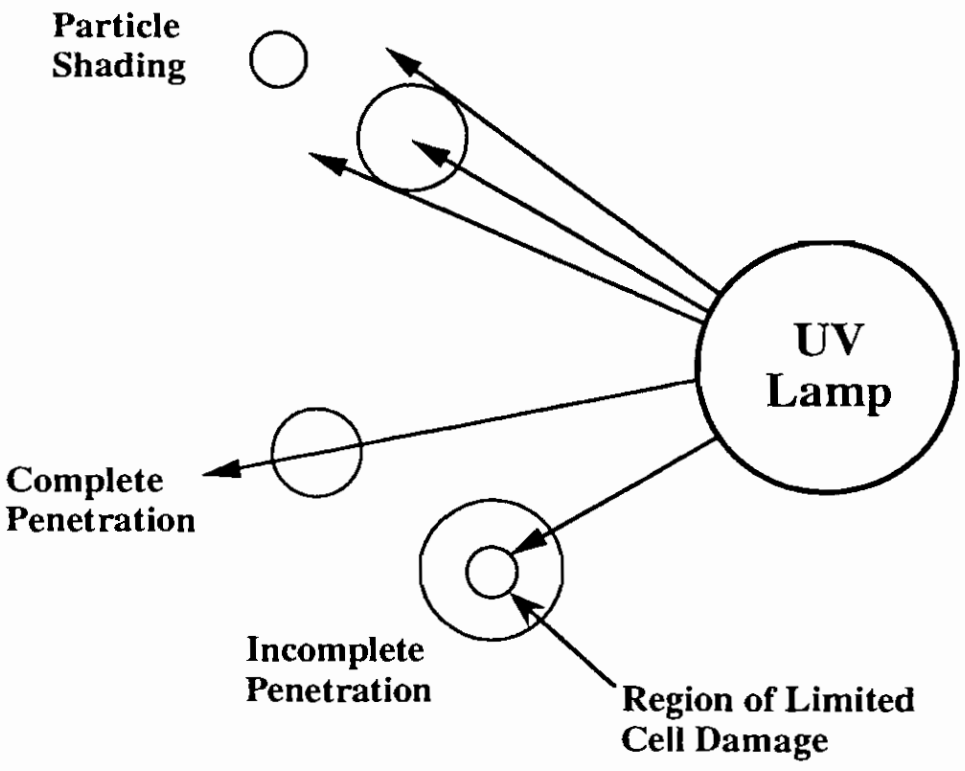
In high-quality wastewaters, the determining factor in predicting UV disinfection performance has been the ability of light to penetrate the wastewater. This ability is primarily determined by the percent transmittance (%T). By measuring the %T of the wastewater, and knowing the reactor geometry and the output of the UV source, the average intensity within the reactor can be determined. The dose delivered to the wastewater is then calculated as the average intensity multiplied by the time of exposure. However, with lower quality wastewaters (e.g., those with high suspended solids), a critical complication arises: the decrease in the ability of the UV light to penetrate suspended solids and inactivate microorganisms within their interior. This phenomenon is discussed in the following section.

The necessary dose varies with the level of disinfection required. Several full-scale plants requiring an effluent fecal coliform bacterial density of 200 per 100 mL have been designed

to provide a dose of approximately 30 mW-s/cm^2. To date, UV disinfection has not been used to meet the most stringent California Wastewater Reclamation Criteria (Title 22) under which the 7-day median of total coliforms should not exceed 2.2 per 100 mL, and a 23 total coliforms/100 mL standard should not be exceeded in more than one sample within any 30-day period. A study completed recently by the University of California at Davis (Snider *et al.* 1991) demonstrated that a dose of 60 mW-s/cm^2 was sufficient to provide unfiltered wastewater effluent not exceeding 23 total coliforms/100 mL. For the filtered wastewater, the 7-day median of 2.2 total coliforms/100 mL and a 30-day standard of no more than one sample exceeding 23 total coliforms/100 mL were consistently met at a UV dose of 97 mW-s/cm^2.

UV dosage is controlled at full scale plants by flow pacing and turning standby lamp banks on or off, depending on the need. The plants are equipped with intensity monitors which provide plant operators with a relative measurement of the dose and warning signals if the intensity provided by the lamps is out of the normal range. The intensity monitor reading is an arbitrary measurement which is proportional to the UV dose, but does not provide the absolute dosage measurement. The monitor provides only a single measurement for an entire UV reactor. Multiple location measurements are required to determine changes of UV intensity patterns within a reactor and to determine an average dose. Additionally, the sensor surface becomes eventually coated and its reading will underestimate the actual intensity provided inside the reactor. Therefore, continuous measurement of an actual UV irradiation dose for full-scale applications is not always practical.

Effect of Suspended Solids and Turbidity. Particulate materials can absorb UV light and cause shielding, thus lessening the UV intensity in the reactor and at least partially protecting the microorganisms from the UV light (Harris *et al.*, 1987a). The effects of particles on UV disinfection are illustrated schematically in Figure 2-3. Qualls *et al.* (1983) reported that coliforms retained by an 8 μm filter were highly resistant to UV light, presumably due to their shielding by the suspended solids. Conversely, the coliform bacteria filtered through an 8 μm filter were much more susceptible to UV irradiation (approximately by 1 log inactivation) than those present in the samples filtered through a 70 μm filter. Qualls *et al.* (1983) concluded that coliforms associated with particles were partially protected from UV disinfection. The effect of particle size distribution on the UV disinfection process has not been studied extensively, but is being investigated by Darby *et al.* at the University of California, Davis as part of a Water Environment Research Foundation grant.



EFFECT OF PARTICLES ON UV DISINFECTION (Snider *et al.* 1991)

FIGURE 2-3

The effect of turbidity on coliform kills is usually not reported for existing full-scale UV irradiation plants because total suspended solids are typically monitored instead of turbidity in secondary treatment plant effluents. However, the relationship between bacterial inactivation efficiency and turbidity may be very similar to that between suspended solids (SS) and bacterial inactivation. Both turbidity and SS are parameters that reflect the concentration of particulates in wastewater. Both of them will explain, crudely, the efficiency of bacterial inactivation that is related to the UV transmittance of wastewater and microorganism shielding by the particles. The deficiency of total suspended solids and turbidity measurements in predicting microbial inactivation is due to ignoring particle size distribution by both parameters. The presence of large-size particles in disinfected water would likely result in greater microbial shielding and lower inactivation rates. Thus, measurement of particle size distribution and correlating it with microorganism survival rate would likely offer a better predictor of process performance than do either total suspended solids or turbidity. Nevertheless, even gross parameters like turbidity and suspended solids may be reliable indicators of UV transmittance in a given treatment plant if the types of solids present in waste effluent do not vary (Severin, 1983). For example, Harris *et al.* (1987a) determined in their study that turbidity was a good surrogate measure for both UV absorbance and log fecal coliform survival.

UV absorbance. UV absorbance at 253.7 nm appears to be the most consistent water quality parameter related to disinfection efficiency (Harris *et al.*, 1987a; Severin, 1980; Scheible *et al.*, 1986; Petrasek *et al.*, 1980). The UV absorbance results from the absorbance of the liquid and dissolved substances as well as from the particles suspended in the liquid phase. Yip and Konasewich (1972) listed many chemical substances that interfere with UV transmission at 253.7 nm. These substances included phenolic compounds, humic acids, lignin sulfonates and ferric iron. No general relationship between the color of water and UV absorbance (transmittance) has been established (Huff *et al.*, 1965) and it is not likely that a general relationship exists. Rather, a site specific relationship between those two water quality parameters may be established as long as color inducing substances contribute to the absorbance at 254 nm (Cairns, 1991). Johnson and Qualls (1985) reported that UV absorbance was associated more with smaller particles and dissolved substances than with larger particles. It appears also that not all particles present in wastewater absorb UV light. For example, Qualls *et al.* (1983) theorized that clays merely scatter UV light and, therefore, do little to inhibit disinfection performance.

In the case of UV disinfection, (a physical rather than a chemical process), it is only UV absorbing species which absorb light in the same wavelength as the nucleic acids (the target molecules of UV disinfection) that can interfere with light penetration to deeper layers. A typical fecal coliform transmits about 70% of the UV light at 254 nanometers (the disinfecting wavelength for most UV light systems currently used in wastewater treatment). The transmitted light is available to inactivate underlying layers of microorganisms. Organics and inorganics adsorbed to the microorganism surface may further reduce the transmittance. Thus, knowledge of the percent UV absorbance of the suspended solids is as important as the measurement of the percent UV absorbance of the bulk wastewater.

Wastewater Temperature. UV lamp intensity depends on the temperature; lamps achieve their greatest output at lamp wall temperatures near 41°C (Koller, 1965). Cortelyou *et al.* (1954) determined that the UV lamps which were directly immersed in water at a temperature between 0°C and 10°C had an output of 22 to 58 percent of that achieved at 20°C (Snider *et al.*, 1991). Those results indicate a great importance of the lamp wall temperature on the overall efficiency of the UV disinfection process. However, in modern submerged quartz tube systems, the tubes are provided with a layer of air insulating the lamp wall from the effect of wastewater temperature. For these lamps, the temperature of wastewater varying between 5°C and 35°C had a negligible effect on UV disinfection (Severin, 1983). No effect of wastewater temperature on UV disinfection was reported by Yip and Konasewich (1972), Johnson and Qualls (1985), and Scheible and Bassell (1981).

Wastewater pH. No effect of pH on the efficiency of UV disinfection was detected by Yip and Konasewich (1972) nor by Scheible and Bassell (1981). This is a very significant advantage of UV irradiation over chlorination which is substantially affected by pH.

Iron and Hardness. Iron affects UV disinfection by: (a) absorbing UV light in the wastewater, (b) precipitation on the quartz sleeves and absorption of UV light before it enters the wastewater, and (c) adsorption of iron onto suspended solids and clumps of bacteria and shielding microorganisms. A level of 0.3 mg/L of iron has been adopted by the industry as the maximum allowable level, but there is no data to substantiate this limit. (Whitby and Palmateer, 1991). Hardness affects UV disinfection because calcium and magnesium salts crystallize out on the quartz sleeve which surrounds the UV lamp preventing the UV light from entering wastewater. Effluents with high iron or hardness require special cleaning for the lamps.

Photoreactivation

The inactivation of microorganisms by UV irradiation results primarily from the absorption of the light by their DNA and the resultant dimerization of thymine bases in the DNA. Subsequent exposure of UV-damaged cells to visible light wavelengths above 300 nm may often repair much of the damage done to the DNA. This light-activated enzymatic pyrimidine monomerization process is called photoreactivation (Jagger, 1967; Palmateer and Whitby, 1987). Many different organisms can undergo photoreactivation (Stover *et al.*, 1986; Harris *et al.*,1987b; Harris *et al.*,1987a; Scheible *et al.*, 1986; Scheible and Bassell, 1981; Johnson and Qualls, 1985). For example, total and fecal coliform groups will exhibit photorepair, while the enterococcus group will not (Scheible, 1989). Viruses lack the repair enzymes necessary for the repair process, and thus photoreactivation is not associated with viruses (Harris *et al.*, 1987b). Repair of microorganisms in the dark was also reported but its extent was lower than for photoreactivation (Whitby *et al.*, 1984; Petrasek *et al.*, 1980).

Most of photoreactivation studies have been conducted in the lab or in enclosed containers. Scheible and Bassell (1981) placed bottles of UV irradiated effluent in the clarifier of a wastewater treatment plant for one hour and found that the number of fecal and total coliforms increased by one logarithm. Whitby *et al.* (1984) placed bottles of UV irradiated effluent in a clarifier and found that after three hours the fecal and total coliforms increased by a maximum of one logarithm. The fecal streptococci and *Pseudomonas aeruginosa* did not photoreactivate. Harris *et al.* (1987b) showed in a laboratory study that *E. coli* and *Streptococcus faecalis* had the potential to photoreactivate and increase their densities by 3.4 and 2.4 log, respectively. Very limited, or no photoreactivation of total coliform bacteria was observed by Snider *et al.* (1991) when the standard of 2.2 total coliforms per 100 mL was achieved in the UV plant effluent. Presumably, the UV doses were so high and bacterial concentrations so low that photoreactivation did not occur. Mechsner *et al.* (1991) investigated long-term reactivation of *E. coli* in drinking water systems under light and dark conditions. A substantial regrowth of bacteria was observed over a period of several days of storage in light as well as in complete darkness. Regrowth was enhanced in waters containing residual organic matter.

Whitby and Palmateer (1993) investigated the effect of UV transmission and the suspended solids on photoreactivation of UV irradiated fecal coliform samples. The ratio of

photorepaired to nonphotorepaired microorganisms did not correlate very well with either UV transmission or suspended solids. It was, therefore, concluded that UV transmission and suspended solids did not effect the degree of photoreactivation.

The practical significance of photoreactivation for UV disinfected wastewater effluents is difficult to assess. Microorganisms released to the receiving water are more likely to face some or all of the following non-ideal conditions: limiting availability of light, limiting supply of nutrients, predation by other organisms, adhesion, sedimentation, or even additional damage by solar UV irradiation. Palmateer and Whitby (1987) compared the degree of photoreactivation of an antibiotic resistant strain of *E. coli* occurring in bottles filled with a UV plant effluent (bottles were suspended 30 cm below the river surface), and in river water sampled from the UV plant effluent dispersion plume (indicated by a tracer dye). The strain of *E. coli* was spiked at the influent of the UV plant to provide UV irradiated bacteria and was also spiked at the UV plant effluent to provide non-irradiated control bacteria. In the bottles suspended below the surface of the river, the concentration of irradiated *E. coli* increased by 1.9 times whereas the density of non-irradiated *E. coli* decreased. In the river, however, the concentration of both irradiated and non-irradiated *E. coli* steadily decreased following exactly the same pattern. Thus, if photoreactivation had occurred, other factors negated any increase of bacterial density.

Present design criteria for UV systems take potential photoreactivation into account by sizing the equipment to provide an additional log inactivation beyond required effluent conditions (Scheible, 1989). At the present time, none of the states allowing UV disinfection of wastewater requires the photoreactivation phenomenon to be taken into account in the NPDES permits (Cairns, 1991).

REACTOR CONFIGURATION AND ITS EFFECT ON UV DISINFECTION

This section describes the development of UV irradiation for wastewater disinfection in the U.S. in 1980s, the effect of UV reactor configuration on the operation and maintenance of UV disinfection systems and on microorganism inactivation efficiency. The advances in UV lamp technology are reviewed next with the emphasis on potential impact for large UV facilities. The modeling of UV disinfection is then discussed based on available information about reactor hydraulics and wastewater quality.

Development of UV Irradiation for Wastewater Disinfection

A 1984 survey identified 53 operating UV wastewater disinfection plants (Scheible, 1989). Of these facilities, 80 percent had design flows less than 1 mgd. In 1988, there were approximately 300 plants in operation in North America. Of 177 plants for which information was available, 59% had design flows less than 1 mgd, 38% between 1 and 10 mgd, and 3% had capacities greater than 10 mgd. The largest operating plant in the U.S. is located in Madison, Wisconsin, with a design peak flow rate of approximately 100 mgd (Scheible, 1989). Other large plants that will begin operation in 1992 include Quebec City (two plants: 90 and 106 mgd peak flow) and Raleigh, NC (120 mgd peak flow). In 1991 there were reportedly 700 UV plants operating in North America (Cairns, 1991). The comparison of these surveys illustrates the changes in the UV disinfection plant design and the increasing acceptance of this process by the industry, primarily in eastern United States. Relatively fewer UV facilities for wastewater treatment are located in the western United States. The majority of the plants located outside California do not provide reclaimed water as defined by the California Administrative Code. However, several plants located in the Northeast discharge their effluent to bays inhabited by shell fish. The first plant operated continuously in California is located in Pacifica near San Francisco. This plant has been operated as a pilot plant and recently has started operating on a permanent basis (Cairns, 1991).

The U.S. experience in UV disinfection of wastewater is far superior to European experience due to the fact that wastewater in Europe has not been typically disinfected prior to discharge. Conversely, many UV disinfection plants for drinking water applications have been operated in Europe.

Reactor Configuration

Several designs of UV contactors have been applied to the disinfection of wastewaters. Closed vessel reactors using thin-walled Teflon pipes, originally developed for drinking water applications, tended to dominate the market through the mid-1980's. They were difficult to maintain and suffered from large pressure drops due to accumulation of debris on the UV lamps because the water flowed perpendicular to the lamps. The entire pressurized system had to be shut down to change a lamp or other components and this necessitated having one hundred percent backup. The closed vessel reactors are generally not considered for new wastewater applications.

The most important development in UV design for wastewater was the modular open channel system with the flow of water parallel to the submerged UV lamps. When the water flows parallel to the UV lamps, debris can only catch on the front or back of the lamp rack where it can be removed by a high pressure hose. The lamps can be either fixed in place or inserted in modules that can be easily removed from the channel. The fixed open channel units reflect earlier designs that suffered problems with accessibility and maintenance; these are no longer installed in favor of the inserted module-style contactor (Scheible, 1989). The modular system allows for any component to be replaced without shutting down the entire system. The open channel modular system using weatherproof components also eliminates the need for pumps and buildings. With this design, a chlorine contact chamber can be converted into a UV disinfection channel.

Reactor Hydraulics. Plug flow conditions are desired in UV disinfection reactor design to minimize short-circuiting. Short-circuiting in the reactor is likely to hinder measurement of UV dose as well as decrease the effective dose applied to some portions of wastewater (Qualls and Johnson, 1985). Conversely, radial turbulence (perpendicular to the flow path) is needed to produce adequate mixing in the non-uniform UV light intensity field (Scheible, 1987; Cortelyou *et al.*, 1954) and to reduce the incidence of particles shading one another from the lamps.

UV Lamp Technology and Maintenance

In modern UV disinfection units, lamps are placed in the stream of flow (submerged quartz tube design) or water flows inside the tubes located between the array of lamps (Teflon tube design). Scheible *et al.* (1986) and Qualls *et al.* (1989) reported better disinfection efficiency using the submerged quartz tube design. Harris *et al.* (1987a) reported lower survival of total coliforms using the submerged quartz tube design but nearly identical results from both designs for fecal coliforms and fecal streptococcus. Harris *et al.* (1987a) also reported higher photoreactivation with the quartz tube design. A reflective covering (either stainless steel or polished aluminum) for the UV disinfection unit is desirable to maximize the utilization of the light. The spacing of the lamps within the submerged quartz tube reactor can have an effect on UV disinfection. Conflicting results are reported as to the performance of closely spaced lamps versus designs with lamps placed apart (Johnson and Qualls *et al.*, 1985; Scheible *et al.*, 1986).

For most disinfection applications, UV light is generated by low pressure mercury vapor lamps. These lamps produce nearly monochromatic light, within six nanometers from a wavelength of 253.7 nm, which is optimal for biocidal effects. Low pressure mercury lamps have a UV output of approximately 0.2 W/cm of arc length at a wavelength of 254 nm. Recently, medium pressure mercury lamps have been tested. Medium pressure mercury lamps have an average UV output of 9 W/cm of arc length at wavelengths below 380 nm. If all of these wavelengths below 380 nm were equally effective in inactivating microorganisms, a medium pressure mercury lamp would have 45 times as much germicidal power than low pressure lamp. The actual ratio between the two types of lamps may be very specific for each effluent, depending upon its absorption spectrum. For example, iron contained in wastewater would readily absorb UV light generated by either type of lamps. The low pressure lamp required a dose four times greater than that for a medium pressure lamp to achieve same 200 fecal coliform/100 mL standard in a secondary effluent (Whitby *et al.* 1991). Medium pressure lamps grow in popularity because they require smaller reactors, which is an advantage in larger installations (Havelaar *et al.* 1990).

Lamp Maintenance and Replacement. The accumulation of solids onto the surface that separates wastewater from the lamps can reduce the intensity of UV light. Scale buildup of calcium, magnesium, and iron has been reported (Harris *et al.*, 1987a). The rate of lamp coating and associated cleaning frequency depends on the quality of treated effluent, and therefore is site-specific. A relationship between intensity reading and the level of disinfection achieved provides a guide to establish cleaning frequency. Periodical chemical cleaning in conjunction with ultrasonic and mechanical wiper cleaning systems was recommended for designs available several years ago (Scheible *et al.*, 1986).

Several UV wastewater disinfection plants were surveyed to obtain information about lamp cleaning frequency and procedure as well as information about lamp replacement. The results are summarized in Table 2-2. The cleaning frequency tended to be based on a set daily or weekly routine, rather than by monitoring a deterioration in performance. Some plants performed cleaning by removing lamp modules and dipping them in an acid bath. Closed vessel plants (e.g., Madison, WI) have an in-place citric acid cleaning system. None of the plants interviewed wiped the lamps during cleaning, nor did they have any mechanical wiping system to supplement the acid bath. Instead, workers hosed off the bulbs before or after acid cleaning. Mechanical wipers have not proven effective and the consensus is that they either do not work or are unnecessary.

TABLE 2-2

CHARACTERISTICS OF SELECTED UV FACILITIES

Facility	ADWF (mgd)	Level of Treatment	Disinfection Permit (per 100mL)	Lamp Cleaning Frequency (each lamp)	Lamp Life	Comments
East Chicago, IN	15	Tertiary	200 FC	6 months	1-2 yrs	Very pleased with system High reliability
Hutchinson, KS	7	Secondary	200 FC	1 week	>2 yrs	High reliability No violations
NW Bergen CVA, NJ	7.5	Secondary (Nitrified)	200 FC 33/61 Enterococcus	2 months	>1 yr	Very pleased with system High reliability
Wausau, WI	5.5	Secondary	400 FC	5 months	>1 yr	Bulb design flaws promote burnout-some violations resulted Comparable labor to chlorine
Windsor, ON	9	Secondary	200 FC	Daily Flushing, Annual Acid Bath	>1.5 yr	Algae problems require daily flushing Labor intensive
York, PA	13	Tertiary	100 FC	3 months	>2 yrs	Satisfied with performance High reliability
Madison, WI	50	Secondary	400 FC (monthly geometric mean)	3 weeks, citric acid for 1 hour		Enclosed teflon units of older design. Units plugged by residual debris. Seasonal operation (May-Oct). Accumulation of algae
Henniker, NH	0.5	Secondary	240 TC			
Hanover, NH	1.2	Secondary	240 TC	1 week acid wash	2 yrs	Plant designed for 200 fecal coliforms. Violations during plant upsets. Very pleased with system

ADWF: Average daily wastewater flow.
FC: Fecal Coliforms.
TC: Total Coliforms.

The majority of UV lamps installed at a treatment plant are continuously lit to provide disinfection. Standby lamp banks are normally turned off; they provide additional UV dose when necessary during peak flows or during unusual water quality conditions, as will be discussed in further sections. Manufacturers recommend that the frequency of turning standby lamps on and off be limited to a few times per day. This frequency should be more than sufficient for a properly operated UV system and insure the long service of the UV lamps. Increased frequency of switching the lamps on and off; e.g., every hour, would result in shortening lamp life.

With regard to spent lamp disposal, there does not appear to be a well-established recycling program for these lamps. Lamps are disposed to municipal landfills with the general trash generated at the treatment facility.

Modeling of UV Disinfection

The following first-order kinetic expression has been used to model bacterial inactivation (Scheible, 1987):

$$N = N_0 \exp(-kIt)$$

where:

- N = bacterial density after exposure to UV light (MPN/100 mL),
- N_0 = initial bacterial density (MPN/100 mL),
- k = inactivation rate constant ($cm^2W^{-1}s^{-1}$),
- I = intensity of the UV light energy (W/cm^2),
- t = exposure time (s).

Although the first-order expression is generally a good first approximation of the response to a given dose, deviations from ideal first-order kinetics may include: (a) lag in the initial response to UV radiation attributed to the initial bacterial resistance, and (b) reduced efficiency of disinfection at higher UV doses due to the aggregation of microorganisms or the occlusion of bacteria in particulate matter. Understanding and predicting the effects of the deviation from first order kinetics occurring at higher UV doses (often called "tailing"), attributed to the shielding of bacteria by particulate matter present in wastewater, is especially important because the UV disinfection plants apply doses in the "tailing" region

of the dose response curve. Scheible (1987) accounted for this phenomenon by adding a term related to bacterial density associated with particulates:

$$N = N_0 \exp(-kIt) + N_p$$

where:

N_p = density of viable (non-inactivated) bacteria associated with particulates (MPN/100 ml).

The term N_p quantifies the effect of particulates by relating it to the effluent suspended solids:

$$N_p = c\ SS^m$$

where SS denotes concentration of suspended solids (mg/L) and c and m are empirical coefficients derived from a log-log regression of effluent bacterial density and suspended solids (Scheible, 1987). These data must be generated under very high dose levels, such that the residual density can be attributed to those bacteria which were occluded from the radiation. Studies conducted at several plants show considerable variability of data (Scheible, 1989) which is likely due to ignoring the particle size distribution of the suspended solids.

Qualls *et al.* (1985) found that the density of surviving bacteria continued to decrease in samples exposed to high UV doses which indicated that the particles did not provide complete protection from the UV light. Furthermore, they found that the suspended solids removed by a 10 μm screen filter predicted the survival of bacteria much better than the conventional total suspended solids measurement. The statistical correlation between these two variables was better than the correlations determined between the bacterial density and total suspended solids, turbidity, the concentration of particles larger than 40 μm, and the suspended solids of the 10-μm filtrate. The authors postulated that the measurement of suspended solids removed by the 10 μm filter could provide a predictor of the performance of UV disinfection Qualls *et al.* (1985). They postulated further that the survival rate could be modeled as a sum of three first-order decay rate terms, each representative of a different class of microorganisms: (a) microorganisms not associated with the particles, (b) those associated with small particles (e.g., below 10 μm), and (c) those associated with large

particles (e.g., above 10 μm). The regression model of survival could be incorporated into a UV reactor model (Qualls *et al.*, 1985; Qualls and Johnson, 1985). This approach to modeling the effect of particles on UV disinfection offers an alternative to the model of Scheible (1987).

A similar approach can be offered based on the electronic measurement of particle size distribution of the suspended solids. If this approach is successful, future on-line continuous monitoring of particle size distribution (a technology that is now available, although not widely used) would provide fast feedback information for process control and/or design. The result of the focus on particle size distribution would be a better understanding and control of UV disinfection. Additionally, emphasis could be placed on removing large particles rather than indiscriminately removing particles of all sizes, which would provide designers and operators with optional approaches to improve disinfection performance.

The model based on the first order kinetics and corrected for the presence of suspended solids still assumes an ideal plug flow in the reactor with no axial dispersion. Under actual conditions, axial dispersion and velocity gradients will cause a distribution of residence times. The disinfection model reported in the Wastewater Disinfection Manual (EPA, 1986) incorporates dispersion effects into the rate expression:

$$N = N_0 \exp\left\{\frac{ux}{2E}\left[1 - \left(1 + \frac{4KE}{u^2}\right)^{1/2}\right]\right\} + N_p$$

where u = velocity of wastewater through the reactor (cm/s),
x = average distance traveled by water while under exposure to UV light (cm),
E = dispersion coefficient (cm^2/s).
K = the inactivation rate constant (1/s).

The dispersion coefficient, E, is a key parameter defining the hydraulic behavior of the contactor. It should be estimated from the tracer test analysis. Inactivation rate, K, is a function of the average light intensity in the UV reactor:

$$K = a\,(I_{avg})^b$$

where I_{avg} is the average reactor intensity, whereas a and b are empirical coefficients specific to wastewater conditions and reflecting the sensitivity of the organisms to UV. Average intensity is a function of the lamp density in the reactor and the UV absorbance characteristics of wastewater. There is no method to directly measure the actual intensity within a complex, multi-lamp reactor. Solutions for computational schemes have been developed and are presented in the Design Manual (EPA, 1986) for a number of system configurations. Determining the rate coefficient, K, for a specific application requires influent/effluent bacterial sampling over a range of intensity levels.

RELIABILITY OF UV DISINFECTION

This section addresses the reliability of UV disinfection systems during high wastewater flows and deteriorated water quality. The reliability of the system is based on equipment redundancy. The emergency safeguards provided at UV irradiation plants and safety of the process are then reviewed.

Process Performance During High Flows and Deteriorated Water Quality

Diurnal and wet weather flow variations are handled by automated systems that open up channels and turn on UV lamp banks as appropriate in relation to measured flow rates. These systems reportedly work well and overflow bypass channels maintain appropriate flow levels under peak wet weather conditions. These same systems can be used during spikes of suspended solids (or turbidity) and during increased density of coliform bacteria in the influent to the UV disinfection unit. It would be very difficult to design a system which would handle any upsets of the upstream processes like, e.g., activated sludge upset due to a toxic spill. Nevertheless, UV systems are designed with redundancy which provides for additional disinfection during abnormal operating conditions. Examples of the performance of the UV plants over a long period of time, including operation during plant upsets and at various suspended solids level, are provided in the next section.

Redundancy of Equipment. UV systems are modular in design (module = rack of lamps) and can be grouped in clusters of modules called banks. Banks are typically arranged in series, and redundancy is provided by installing an additional standby bank in the series; this allows also for one complete bank to be removed for maintenance. Alternatively, 100% redundancy can be provided by a parallel set of banks.

UV system design incorporates the worst case scenario taking into account factors including: (a) lowest UV transmittance of treated effluent, (b) lamp aging, (c) lamp operation at low temperatures, (d) peak flow rates, (e) highest influent bacterial density, and (f) elevated suspended solids concentration. UV systems are designed for the amount of equipment required to achieve the target disinfection level under the worst case scenario, plus one additional bank to provide redundancy for other banks taken out of service.

Large diurnal fluctuations of flow are handled by flow pacing which involves the use of several UV lamp channels needed to accommodate the flow. If water quality temporarily deteriorates beyond even the worst case scenario, but the flow rate is below the peak value, the additional capacity (additional channels or longer retention time in each channel) can be utilized to provide necessary higher doses.

Seasonal Variation of UV Disinfection Efficiency. The efficiency of UV disinfection may vary depending on the season due to a seasonal variation of raw wastewater quality, seasonal upsets of the processes located upstream from the UV disinfection process (e.g., activated sludge), and seasonal UV lamp fouling. However, no generalizations can be made on seasonal variation of UV irradiation efficiency and each case should be investigated separately. Seasonally varying water quality parameters may include: concentration of bacteria and viruses in the raw wastewater, UV absorbance, suspended solids, turbidity, and concentration of organic compounds. In temperate climate, the concentration of microorganisms increases approximately by 1 log during the summer as compared with the winter densities (Cairns, 1991). However, the densities of raw wastewater bacteria did not correlate well with the concentration of microorganisms surviving UV disinfection (Snider *et al.*, 1991). It is possible that the spring runoff and associated elution of the humic acids into the water system may affect the UV absorbance of wastewater for systems with considerable infiltration and inflow to the sewer. Similarly, the turbidity of wastewater could be increased during the storm season. Finally, UV absorbance could also be affected by seasonal industrial activity. These scenarios are speculative and will probably vary depending on the location.

Seasonal upsets of upstream processes may be associated with variation of the food/biomass (F/M) ratio in the biological treatment or seasonal increase in the wastewater flow. This was observed for the plant in Hanover, NH where the plant upsets correlated with the beginning of the academic year at a local university. Seasonal fouling of the lamps

may be the cause for the decrease of the UV plant performance at the end of the disinfection season in Madison, WI. This particular plant, however, is equipped with the old closed-vessel UV system which is not nearly as easy to clean as the new open-channel design, and, therefore, fouling at that plant would not be representative of the vast majority of the UV plants in operation.

Overall, seasonal changes in water quality, seasonal upsets in the upstream processes, and fouling of the UV lamps might affect UV disinfection efficiency. However, a properly operated secondary plant should be capable of reducing the variation of wastewater quality for UV disinfection plant influent. Application of filtration ahead of the disinfection has an additional dampening effect of water quality variations. A properly designed UV plant with sufficient redundancy available, as discussed above, should be capable of producing constant bacteriological quality effluent regardless of any seasonal influences.

Emergency Issues

UV system should include following components to ensure compliance with the disinfection requirements (Whitby and Palmateer, 1991):

- UV specific sensor monitoring lamp intensity; the UV light meter must only measure light at a wavelength of 254 nm; sensors using filters to eliminate visible light may be degraded by moisture and the high intensity of UV light,
- lamp monitoring system which can identify the location of an individual lamp failure,
- individually isolated UV lamps; water cannot enter the entire UV rack if a quartz sleeve or water seal fails,
- UV lamps with electrical connections at one end and single open-ended quartz sleeves; this eliminates fifty percent of water seals and electrical connections,
- a non-resettable hour meter to display actual hours of UV lamp operation,
- low and high water level alarms; a controller of the level of water over the top row of lamps,
- high temperature monitor and cooling,
- protective circuits for overcurrent and ground current leakage detection,
- ground fault interrupters,
- all electrical connectors should be weatherproof and easily disconnected during cold weather,
- bank status display and monitoring.

Power outages can be counteracted by: (a) installing standby power supplies, (b) temporary flow diversion to waste or source, and (c) applying a standby chlorination system.

Safety Issues

UV disinfection systems are completely free of chemical hazards to the public and operator since no toxic chemicals are transported, used or generated in the process. The hazards of the process are low, principally related to the high electrical loads and the potential exposure to the UV light; these are conditions which are easily safeguarded. The lamps do not present a hazard while submerged and operational; the water absorbance will sufficiently attenuate the radiation (EPA, 1986). On-site safety is ensured by equipment designed to avoid stray UV light reaching the operator.

Worker safety precautions during lamp replacement and cleaning include wearing eye protection as a minimum requirement. The workers at some plants also wear a plastic suit and gloves during lamp replacement. The systems are not tamper proof in that it is possible to lift out a lamp module while it is still on, though the power cable limits this movement. Proper removal/replacement practice involves turning the lamp bank off at the control panel, disconnecting the appropriate module, then removal of the module or replacement of the lamps as necessary.

Application of UV Disinfection to Title 22 Effluents

Darby *et al.* (1993) reported recent results of a pilot plant study on the UV disinfection of secondary filtered and unfiltered wastewater to achieve 7-day median standard of 23 total coliform per 100 mL and a more stringent standard of 2.2 total coliform per 100 mL. The results indicated that the standard of 23 total coliform per 100 mL was met consistently in effluent exposed to an average UV dose of 60 mWs/cm^2 or greater and of 48 mWs/cm^2 for unfiltered and filtered wastewater, respectively. The more stringent standard of 2.2 total coliform per 100 mL was met with the UV dose of 97 mWs/cm^2 for filtered wastewater.

DISINFECTION BYPRODUCTS AND WHOLE EFFLUENT TOXICITY

Chlorination By-Products and Effluent Toxicity

The impact of chlorination on the production of by-products has been extensively studied in drinking water. Among the major volatile chlorinated by-products are trihalomethanes, haloketones, and haloacetonitriles (Reckhow and Singer, 1990). Numerous other volatile chlorination byproducts have been identified at trace levels (Krasner *et al*, 1989) and lesser by-products may be major contributors to the mutagenicity of chlorinated waters (Kronberg et al., 1988). Considerably less by-product characterization work has been performed on treated wastewater effluent. Fam *et al* (1987) looked at the nature of the major precursors to observed gas chromatographic , non-volatile chlorination hy-products in a chlorinated, tertiary-treated domestic wastewater effluent. They found that the smaller, polar components that are least likely to be removed were the most reactive with chlorine. Chadik and Pregeant (1992) found that the formation of THMs in a denitrified wastewater treatment plant increased as a function of time and chlorine dose and that chlorine doses sufficient to produce residual concentrations of 1 mg/L of free chlorine yield substantial concentrations of THMs after 1 hour of contact time.

The acute toxicity of total residual chlorine to aquatic life has been well documented through laboratory toxicity testing of power plant and municipal wastewater effluents (Brungs 1973; Bellanca, 1977; Rein, 1992). What is still not fully characterized are the chronic toxicity impacts of low-level chorine residuals and chlorination by-products (Roberts, 1987; Cumming et al, 1979). Some studies have indicated that the addition of sulfur dioxide or hisulfite as a dechlorinationg agent significantly reduces or eliminates chronic toxicity (Rein, 1992), hut the relative doses of chlorine and dechlorinating agent may impact the results.

UV Irradiation By-Products and Effluent Toxicity

The availahle literature indicates that UV irradiation does not contribute to disinfection by-products which would be either harmful to health or adverse aesthetically (Wolfe, 1990). Several studies have shown that UV radiation did not produce increased mutagenic activity in the water. Further, UV treatment of carhon-filtered drinking water did not produce

assimilable organic carbon compounds. UV radiation also did not produce tastes or odors (Wolfe, 1990). Akhlaq *et al.* (1990) reported experiments in which high molecular weight polysaccharide alginic acid solution (used as a model of organic compounds naturally occurring in lakes) was irradiated with UV light; alginic acid was essentially unaffected by UV disinfection.

A newly recognized benefit of UV irradiation is the production of high-energy, short-lived free radicals resulting when UV radiation reacts with ozone or hydrogen peroxide. These UV-based advanced oxidation processes have been shown to be effective in breaking down selected taste and odor compounds and other groundwater contaminants (Wolfe, 1990). The destruction rates of 1,1,1-trichloroethane, trichloroethylene and tetrachloroethylene were increased by an order of magnitude when ozonated water was irradiated with UV light. No volatile organochlorine compounds were formed in these reactions (Kusakabe *et al.* 1991).

In another study (Gurol and Vatistas, 1987), phenol, p-cresol, and 3,4-xylenol were removed non-selectively by UV irradiation in the pH range 7-9. The removal was explained based on the same free radical reaction mechanism as for ozonation of phenolic compounds. The concentration was reduced from 50 to 35 mg/L within 100 min of UV irradiation. No information on potential by-products was presented. Application of UV irradiation also enhanced the oxidation of phenols by ozonation. Gjessing and Kallqvist (1991) postulated that UV irradiation of humic substances initiated chemical reactions that could result in oxidizing compounds such as singlet oxygen, hydrogen peroxide and hydroxyl radicals, which in turn may have toxic effect on aquatic organisms. In general, these reaction products are probably short-lived; however, the interactions may occur for days after the termination of radiation.

Little published research exists on the relative acute and chronic toxicity of UV irradiated effluents. A reduction of in-stream acute fish toxicity was demonstrated for a secondary effluent when chlorine disinfection was replaced by UV radiation (Whitby, 1984). The chlorinated effluent showed complete mortality within 24 hours while the UV irradiated effluent was non-lethal for a 48-hour exposure period. Pilot-scale testing of effluent collected from the City of Akron, Ohio during two high flow events showed an increase in chlorination/dechlorination acute toxicity to fathead minnows and *Ceriodaphna dubia* and no toxicity effects for UV radiation (Rein, 1992).

Chronic toxicity was also investigated during the pilot study in Akron, Ohio. Due to low toxicity exhibited by the influent and disinfected samples, the relative toxicities of the influent and disinfected samples were based on 100 percent effluent samples for *C. dubia.* No toxicity was observed with fathead minnows for any of the samples. Chronic results for number of offspring per adult and percent survival were performed six times over a 3 month period. Chronic toxicity was only exhibited for the chlorination/dechlorination process and not for the UV irradiated effluent (Rein, 1992).

Chronic toxicity from UV irradiated surface water containing high concentrations of humic substances was demonstrated as a decline in the growth of *Selenastrum capricornutum* (Gjessing, 1991). Humic substances are photosensitizers that can transform UV photon energy into highly reactive free radicals thereby greatly enhancing the potential toxicity of the irradiated water (Larson & Berenbaum, 1988). It is unlikely that a significant concentration of humic substances would be present in a secondary effluent and this finding is therefore not applicable.

Researchers at Oak Ridge National Laboratory have published numerous studies investigating the relationship of disinfection to mutagenicity in wastewater effluents. Screening tests such as the Salmonella microsomal mutagenicity (Ames) test were used to demonstrate evidence of mutagenicity. The samples studied consisted of one primary and eight secondary effluents disinfected by chlorine, ozone, or UV radiation. Mutagenic concentrates were then fractionated by high pressure liquid chromatography to attempt to identify the mutagenic components. The results obtained for the five treatment plants utilizing chlorination revealed no consistent trend in mutagencity before and after disinfection. In some effluents chlorination created mutagenicity and in other effluents it decreased mutagenicity. At one plant, the change in mutagenicity following chlorination reversed when measurements were performed during a different season of the year (summer versus fall). In the two plant effluents where UV irradiation was tested at bench-scale or pilot-scale, no effluent mutagenicity was measured before and after disinfection. However, the applied UV doses were low (17 and 21 mW•sec/sq cm). Data was also collected from specific HPLC fractions of the Northwest Bergen County control, chlorinated effluent, and UV irradiated effluent. Although the data showed reduction of mutagenicity by chlorination and elimination of mutagenicity by UV radiation, some mutagenic components may have been lost or destroyed during the HPLC separation process. (Cumming et. al, 1979).

Insufficient published data is available to be able to predict whether chronic toxicity of an effluent will increase or decrease for a disinfection process. It appears that the chronic toxicity produced through the disinfection process is strongly dependent not only on the disinfectant utilized, but also the water quality of the treated effluent. This prevents utilization of one set of study results to a different effluent. Comparative chronic toxicity data for chlorine and UV disinfected effluent is needed to assess the relative toxicity of UV disinfection against the currently accepted technology.

SUMMARY OF FINDINGS

The principal findings of this literature review are briefly summarized below:

- Comparing disinfection efficiencies of UV irradiation and chlorination is difficult because both are fundamentally different processes. Crude comparisons can be made by using *E. coli* as a common reference organism. Using this method, UV irradiation appears to be as effective as free chlorination for virus inactivation in wastewater. This is based on several studies, which showed that approximately equal or, in some cases, lower doses of UV light were required for inactivation of the most resistant viruses (relative to the dose for *E. coli* inactivation) as compared to free chlorination. UV irradiation is much more effective for inactivation of viruses than chloramination.

- The difference in microorganism sensitivity between chlorination and UV irradiation may result from different underlying mechanisms of disinfection. UV light in the wavelength range between 240 and 260 nm kills microorganisms by causing photochemical damage to RNA and DNA. By comparison, disinfection with chlorine appears to involve penetration of the active species through the cell wall to reach various cellular components.

- Several authors recommended F-specific bacteriophages as model organisms for UV virus inactivation in the secondary effluent. The UV light inactivation rates obtained for indigenous F-specific bacteriophage and reovirus were very similar. On the other hand, laboratory propagated F-specific bacteriophage MS2 was inactivated by UV disinfection at a rate which was twice that of indigenous F-specific bacteriophage.

- The available literature indicates that UV irradiation does not contribute to disinfection by-products that may have deleterious health effects. Several studies have shown that UV irradiation did not produce increased mutagenic activity in water.

- Many organisms exhibit the ability to photoreactivate. Repair of cells is initiated by special enzymes that are triggered into action by the energy of visible light. Viruses lack these repair enzymes, and thus photoreactivation is not associated with these organisms. Total and fecal coliform bacteria will exhibit photorepair, while the enterococcus group does not. Present design criteria for UV systems takes potential photoreactivation into account by sizing the equipment to provide an additional log inactivation beyond required effluent conditions.

- For most disinfection applications, UV light is generated by low pressure mercury vapor lamps. These lamps produce nearly monochromatic light near the wavelength optimal for biocidal effects. Recently, medium pressure mercury lamps have been tested. Medium pressure mercury lamps have a much greater output than low pressure lamps but their light is not monochromatic. Medium pressure lamps are capable of delivering much greater UV doses than low pressure lamps, which offers a considerable advantage for plants requiring high UV doses.

- Selected UV wastewater disinfection plants were contacted to obtain information about lamp cleaning frequencies and procedures as well as information about lamp replacement. The cleaning frequency tended to be based on a set daily or weekly routine rather than by monitoring a deterioration in performance. None of the plants interviewed wiped the lamps during cleaning, nor did they have any mechanical wiping system to supplement the acid bath. Instead, workers hosed off the bulbs before or after acid cleaning.

- A past survey of existing UV wastewater disinfection plants indicates the increasing acceptance of this process by the industry, primarily in eastern United States. Plant capacities as high as 100 mgd peak flow rate were reported. Relatively fewer UV facilities for wastewater treatment are located in the western United States.

- The measurement of total suspended solids (TSS) or turbidity provides only a crude indicator of plant performance in terms of bacterial density in the disinfected effluent. A reasonable relationship between the two variables can be determined only if there is a

large variation in TSS or turbidity. Other variables, like UV absorbance of wastewater, influent bacterial density and the size distribution of particulate matter also contribute to plant performance.

- UV dosage is controlled at full scale plants by flow pacing and turning standby lamp banks on or off, depending on the need. The plants are equipped with intensity monitors which provide plant operators with a relative measurement of the dose. Continuous measurement of an actual UV irradiation dose for full-scale applications is not practical.

- The efficiency of UV disinfection may vary depending on the season due to a seasonal variation of raw wastewater quality, seasonal upsets of the processes located upstream from the UV disinfection process (e.g., activated sludge), and seasonal UV lamp fouling. However, no generalizations can be made on seasonal variation of UV irradiation efficiency and each case should be investigated separately. Seasonally varying water quality parameters may include: concentration of bacteria and viruses in the raw wastewater, UV absorbance, suspended solids, turbidity, and concentration of organic compounds.

Section 3

MONTGOMERY WATSON

SECTION 3

EXPERIMENTAL METHODS AND PROCEDURES

To demonstrate the equivalency of UV irradiation to chlorine disinfection, the bacterial and viral inactivation achieved in EVMWD's filtered secondary effluent after UV and chlorine disinfection were measured side-by-side at bench-scale and at full-scale. Details of the full-scale plant modifications, the bench-scale equipment, the experimental conditions, the sampling procedures, the virus seeding protocols, and the analytical methodologies are described below. Also presented is a description of the photoreactivation experiments and full-scale tracer testing.

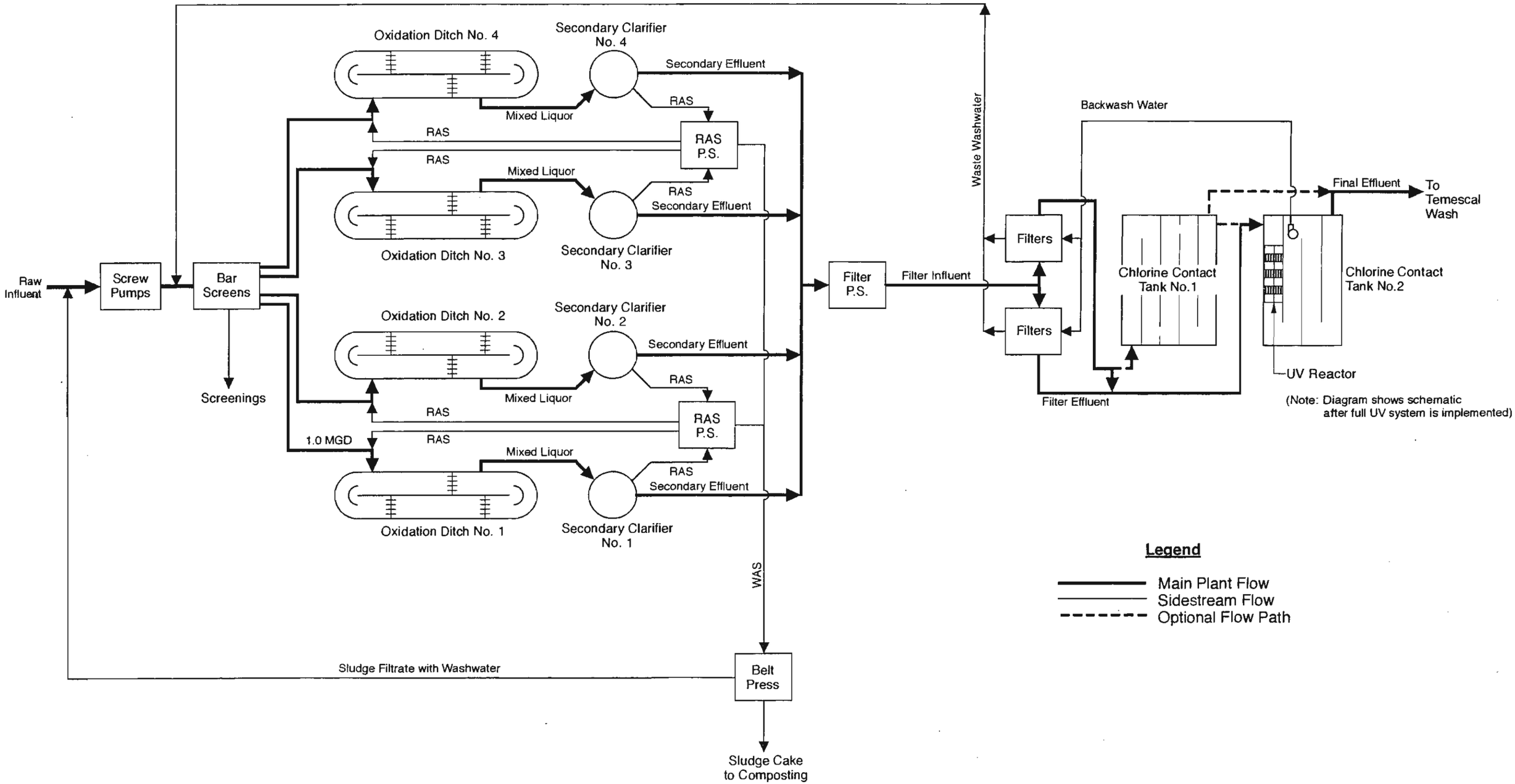
FULL-SCALE PLANT MODIFICATIONS

The layout of the treatment processes at the EVMWD Regional plant prior to the modifications made for the study is shown in Figure 3-1. The plant's second chlorine contactor was retrofit with a Trojan 3000 UV system supplied by Trojan Technologies Inc. of Ontario, Canada. The modifications made to the chlorine contactor and a schematic of the full-scale unit are shown in Figure 3-2.

The Trojan 3000 UV system installed at the EVMWD Regional Plant consists of 5 UV banks. Each bank contains 15 modules and 8 lamps per module for a total of 600 lamps oriented in an axial direction to the effluent flow. Each low pressure mercury discharge lamp has an arc length of 58 inches, and is enclosed in a 0.9 inch diameter quartz sleeve to prevent direct contact with the wastewater effluent. The system was designed to deliver a UV output of 26.7 watts/lamp after 100 hours of lamp operation and an average UV dose greater than 140 mW•sec/sq cm at average daily flow and peak week flow. The UV system design criteria are summarized in Table 3-1. The full-scale unit is equipped with a control panel that includes an elapsed time meter, a UV intensity meter, and LED lamp failure indicator for each bank.

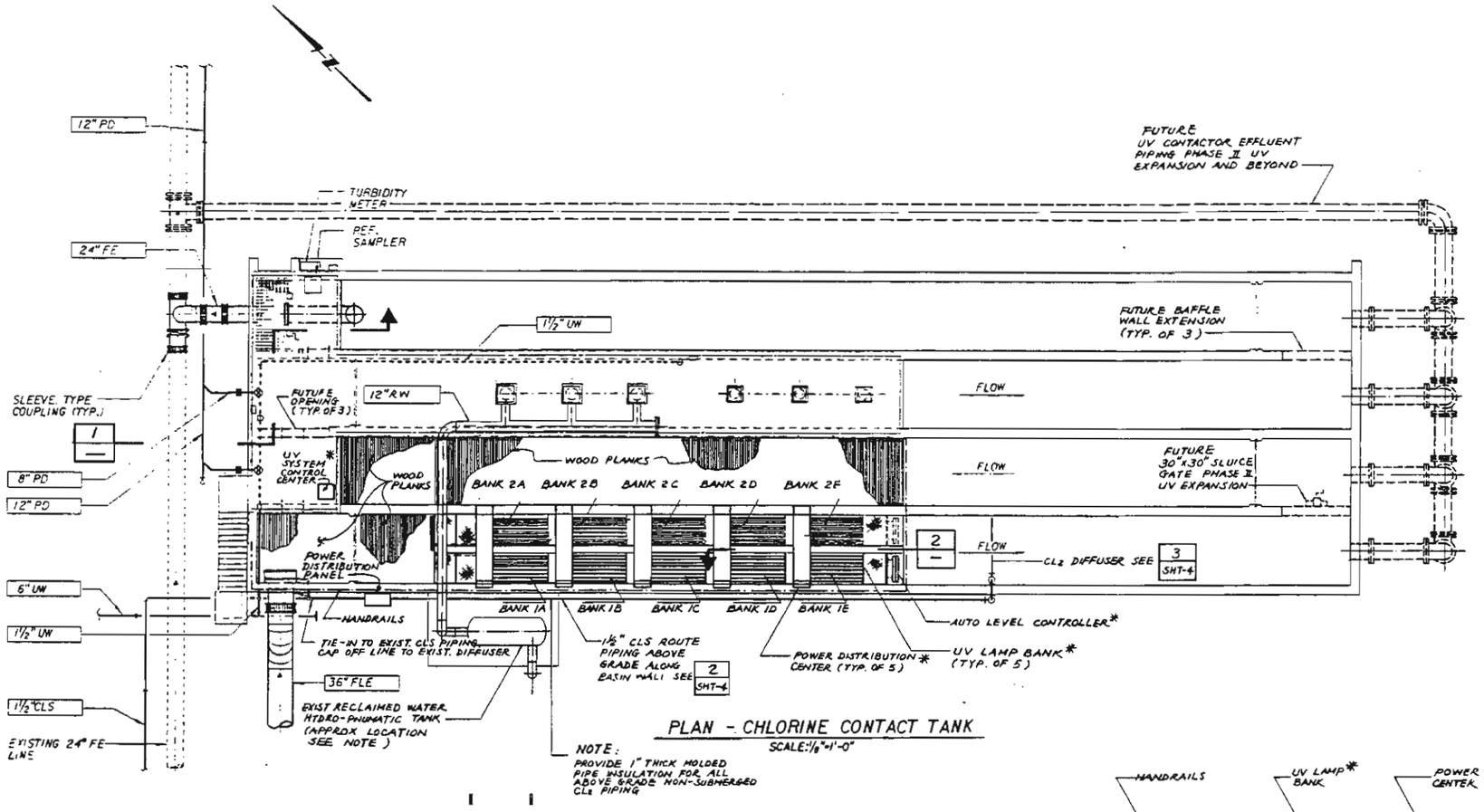
BENCH-SCALE EQUIPMENT

The bench-scale inactivation experiments were performed using a 3-L chlorine batch reactor and three Trojan Model 605 Plus flow-through reactors configured in series. A schematic



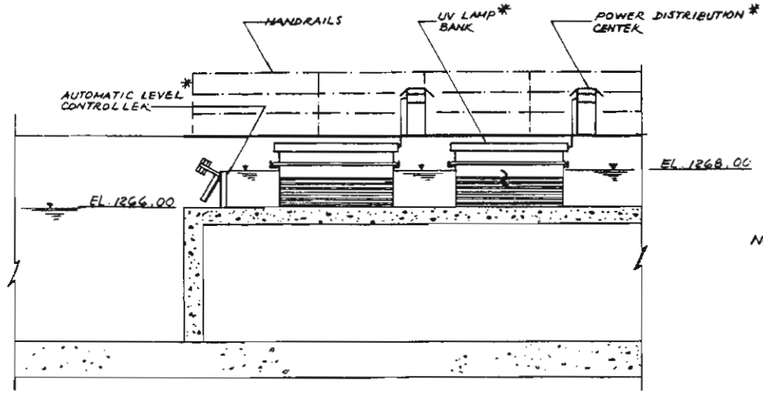
MONTGOMERY WATSON

Elsinore Valley MWD
Regional Wastewater Reclamation Plant
Process Flow Diagram
Figure 3-1



PLAN - CHLORINE CONTACT TANK
SCALE: 1/8"=1'-0"

NOTE:
PROVIDE 1" THICK MOLDED PIPE INSULATION FOR ALL ABOVE GRADE NON-SUBMERGED CL2 PIPING



SECTION 2
SCALE: 1/4"=1'-0"

NOTE:
CONTRACTOR SHALL FIELD VERIFY LOCATION AND DIMENSIONS OF RECLAIMED WATER HYDRO-PNUMATIC TANK TO AVOID INTERFERANCE WITH WORK.

* INDICATES ITEMS PROVIDED BY TROJAN TECHNOLOGIES INC.

REGISTERED PROFESSIONAL ENGINEER AJIT S. BHAMRAH No. 43348 Exp. 6/30/05 CIVIL STATE OF CALIFORNIA

MONTGOMERY WATSON

Elsinore Valley MWD
Regional Wastewater Reclamation Plant
UV Disinfection System Layout
FIGURE 3-2

TABLE 3-1

UV SYSTEM DESIGN CRITERIA

PARAMETER	UNITS	PILOT FACILITY	FINAL FACILITY
Design Flows			
Average Daily Flow	mgd	2.0	4.0
Peak Week Flow	mgd	2.6	5.2
Peak Day Flow	mgd	3.4	6.8
Channels			
Number	-	1	2
Dimensions			
Length	ft	58	58
Width, each	ft	3.75	3.75
Water Depth	ft	2.00	2.00
Lamp Banks			
Number (each channel)	-	4+1	4+1
Modules per Bank	No.	15	15
Lamps per Module	No.	8	8
Lamps per Bank	No.	120	120
Lamp Arrangement	-	3 inch spacing, center to center, unstaggered.	
Lamp Data			
UV Output Power @ 100 hours	Watts/lamp	26.7	26.7
Arc Length of Lamps	inch	58	58
Quartz Sleeve Diameter	in	0.9	0.9
Total Exposure Time (with 4 banks on line)			
Average Day Flow	seconds	43.6	43.6
Peak Week Flow	seconds	33.5	33.5
Peak Day Flow	seconds	26.7	26.7

of the bench-scale UV reactor is presented in Figure 3-3. Collimated beam experiments were performed with MS-2 bacteriophage to obtain a dose-response curve to use as a calibration check of the bench-scale and full-scale UV reactor doses derived from the single point source summation (SPSS) model supplied by the manufacturer. The collimated beam apparatus, shown in Figure 3-4 consisted of 2 inch diameter copper pipe suspended <0.25 inches above a 52 mm petri dish containing 10 mL of the filtered secondary effluent seeded with a pure culture of MS2 bacteriophage. The UV intensity at 254 nm at the water surface was measured with a calibrated radiometer (UVP, San Gabriel, CA).

EXPERIMENTAL CONDITIONS

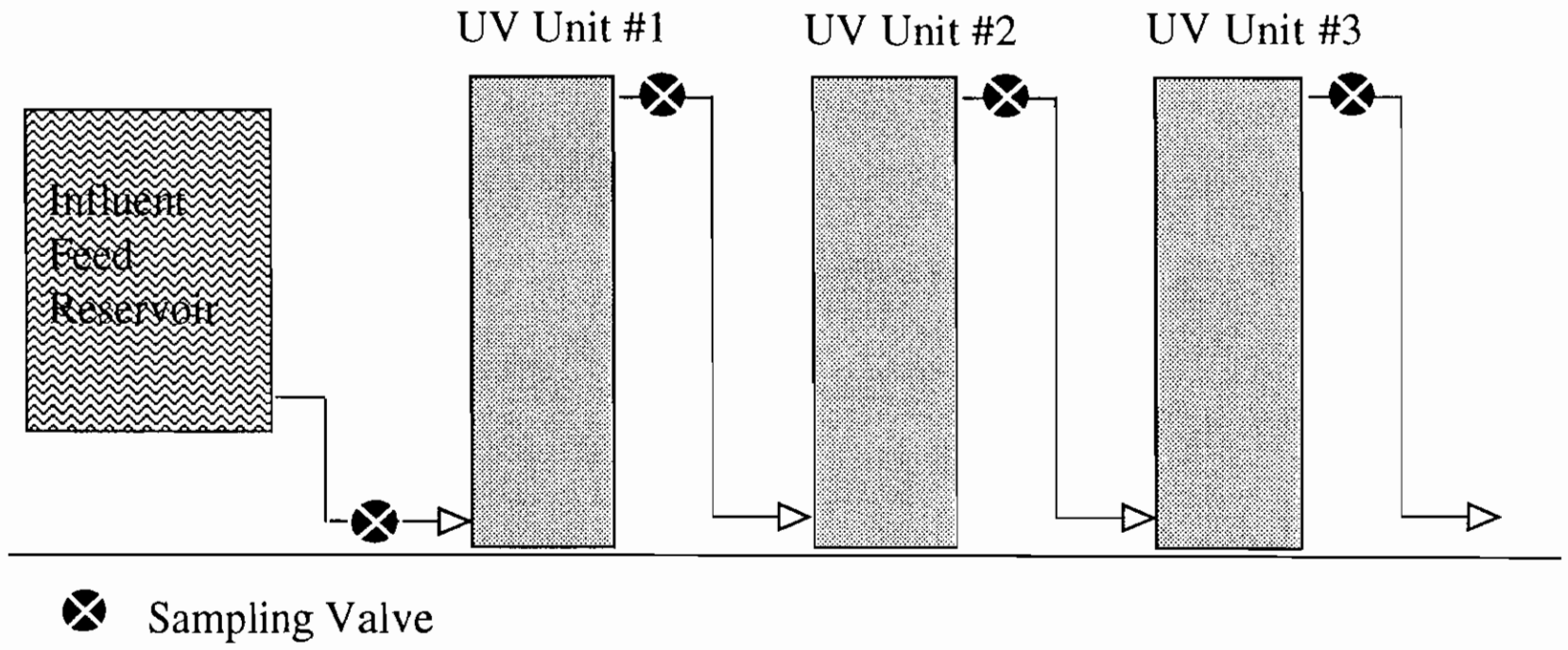
Bacteria and virus inactivation experiments, disinfection by-product characterization, whole effluent toxicity testing, and photoreactivation were performed in accordance with the schedule provided in Table 3-2.

Bench-Scale Inactivation Experiments

Five replicate bacterial inactivation experiments were performed at bench-scale. The UV and chlorine inactivation experiments were performed on the same day using identical filtered secondary effluent collected from the EVMWD Regional Plant. The chlorination experiments were based on a 2-hour contact time. Subsequent chlorine kinetic experiments were performed in August without side-by-side UV testing. The water quality was characterized for each bench-scale experiment. Collimated beam experiments, were used to obtain an MS2 bacteriophage dose inactivation curve to use in calibrating the model calculated dose obtained from the UV bench-scale studies.

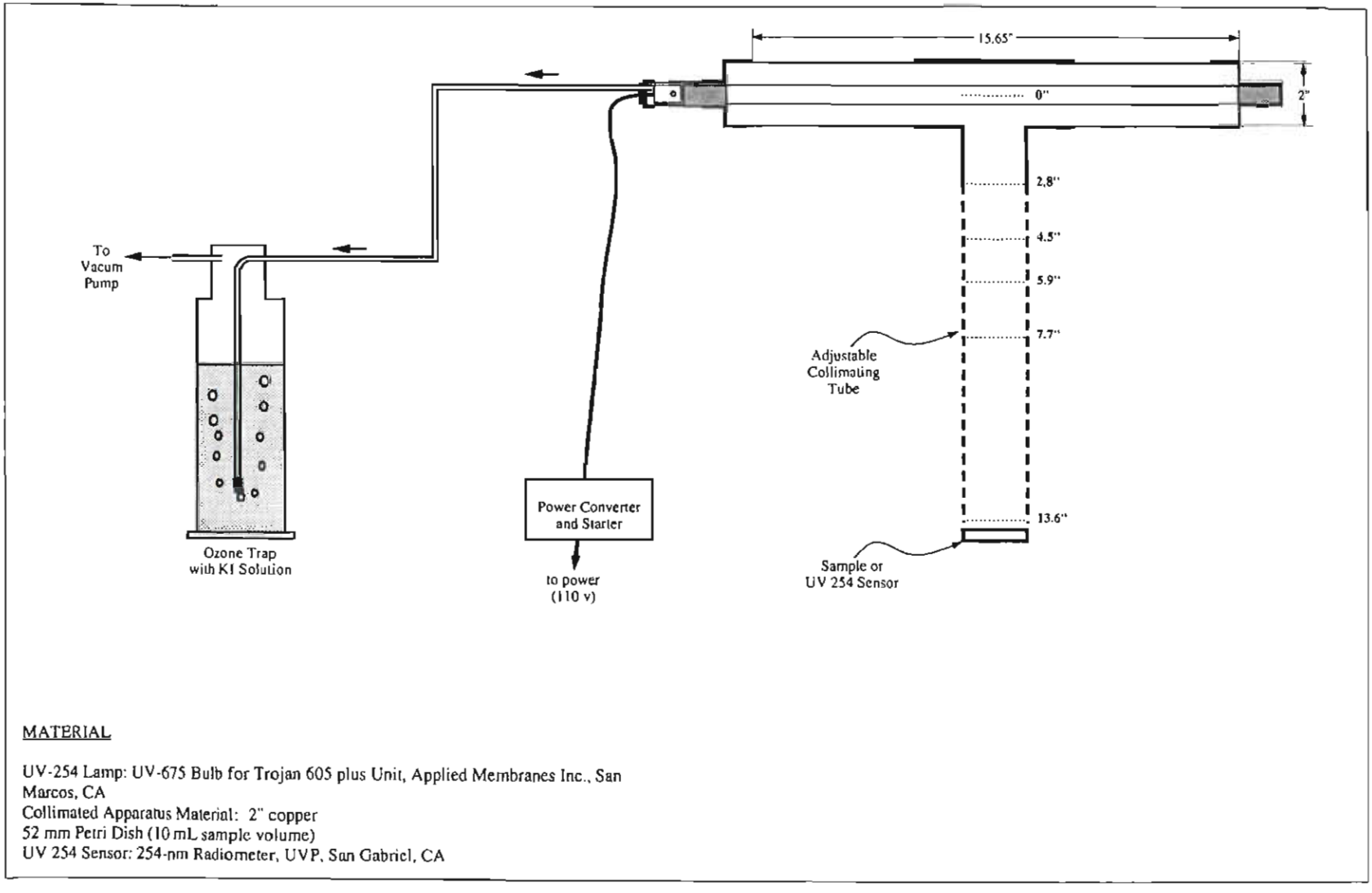
Full-Scale Inactivation Experiments

Twenty-one sets of samples were collected from the Trojan 3000 UV system and the EVMWD chlorine contact basin between January 1993 and September 1993. Influent and five UV irradiated samples (one from each UV bank) and influent plus five chlorinated samples were collected for each experiment with the exception of the September 1993 experiments when only three chlorinated samples were collected. Seven sets of MS2 bacteriophage seedings were performed to allow for an alternative measure of the UV dose which could be compared with the SPSS calculation method. Five sets of polio virus seedings were performed during July 1993 through September 1993. Prior to September



SIMPLIFIED SCHEMATIC OF BENCH-SCALE UV REACTOR

FIGURE 3-3



MATERIAL

UV-254 Lamp: UV-675 Bulb for Trojan 605 plus Unit, Applied Membranes Inc., San Marcos, CA
Collimated Apparatus Material: 2" copper
52 mm Petri Dish (10 mL sample volume)
UV 254 Sensor: 254-nm Radiometer, UVP, San Gabriel, CA

SIDE VIEW OF COLLIMATED UV BEAM APPARATUS

FIGURE 3-4

TABLE 3-2

SAMPLING SCHEDULE SUMMARY

	Full-Scale †	Additional Experiments		Bench-Scale^	Additional Experiments
1	2/10/93		1	10/6/92	
2	2/25/93		2	11/3/92	
3	3/11/93		3	11/24/92	BS
4	3/24/93		4	12/15/92	c
5	4/28/93		5	12/22/92	c
6	5/13/93		6	1/4/92	
7	5/19/93		7	1/7/92	BS
8	5/26/93		8	1/11/93	
9	6/2/93	MS2	9	1/19/93	DBPs
10	6/9/93		10	3/2/93	Polio
11	6/16/93	MS2	11	5/4/93	DBPs, Polio
12	6/23/93		12	6/16/93	DBPs
13	6/29/93		13	7/15/93	Polio
14	7/7/93	MS2, Polio	14	8/4/93	Polio
15	7/14/93		15	8/24/93	Polio
16	7/21/93				
17	7/27/93				
18	8/3/93	MS2, Polio			
19	9/14/93	MS2, Polio*			
20	9/23/93	MS2, Polio*			
21	9/29/93	MS2, Polio*			
22	11/10/93	Title 22 Compliance, DBP, WET			
23	12/6/93	Photreactivation			

† Bacterial inactivation performed for all experimens

^ Bacterial inactivation performed for all experimens except for runs 3,4,5,6, and 13

BS indicates bench-scale UV reactor calibration

c indicates collimated beam UV calibration experiments

MS2 and Polio indicates seeding

* indicates new sampling locations

DBPs indicates sampling for DBP analyses

WET indicates sampling for whole effluent toxicity

30 1993, 60% of the UV lamps were covered with aluminum sleeves to obtain lower UV doses to allow for characterization of the upper portion of the inactivation curves. After this date, the lamps were uncovered and ten consecutive days of sampling were conducted in November, 1993 to determine the minimum UV dose to meet the most stringent Title 22 coliform requirement of ≤2.2 MPN/100 mL. A photoreactivation experiment and full-scale tracer test were conducted during November 1993 and December 1993.

Disinfection By-Product Characterization and Toxicity Experiments

By-product characterization of the disinfected effluents was originally scheduled for the minimum UV and chlorine doses required to achieve 4-log inactivation of indigenous concentrations of the target organisms and consistent reduction of the total coliform density to ≤2.2 MPN/100 mL. In order to expedite the study schedule, the decision was made to initiate the by-product characterization prior to completion of the inactivation experiments. Conservatively high UV and chlorine doses of approximately 2000 mW•sec/sq cm and 10 mg/L of chlorine with a 2-hour contact time were applied at bench-scale to maximize the potential to detect disinfection by-products. DBP characterization of the chlorinated effluent was based on two samples collected on January 19, 1993 and May 4, 1993. DBP characterization of the UV irradiated effluent was based on three discrete samples collected on January 19, 1993 and May 4, 1993 and June 16, 1993. Production of chlorine and UV by-products and whole effluent toxicity at full-scale were also measured by collecting filtered secondary effluent, chlorinated filtered secondary effluent, and UV irradiated filtered secondary effluent from the EVMWD Regional Plant on November 17, 1993.

SAMPLING PROCEDURES

Samples for microbial assay were collected according to the sample collection and storage protocols outlined in Method 9060 of "Standard Methods for the Examination of Water and Wastewater, 19th Edition" (APHA, AWWA, and WEF, 1992). Samples were collected from the downstream end to the upstream end of the plant to avoid possible contamination by the sampling process. A log was kept and all general observations, descriptions of special conditions that were encountered, and notes regarding adjustments made during the sampling procedure were recorded.

Samples for water quality characterization were collected and analyzed according to the sample collection and storage protocols specified by EPA and summarized in Table 3-3.

TABLE 3-3

SAMPLE COLLECTION AND STORAGE PROTOCOLS

Parameter	Container	Preservative	Holding Time
Microbiological			
Total Coliform Bacteria	Autoclaved Polyethylene	Sodium Thiosulfate	24 hours
Fecal Coliform Bacteria	Autoclaved Polyethylene	Sodium Thiosulfate	24 hours
Enterococci Bacteria	Autoclaved Polyethylene	Sodium Thiosulfate	24 hours
Fecal Streptococcus Bacteria	Autoclaved Polyethylene	Sodium Thiosulfate	24 hours
Heterotrophic Plate Count	Autoclaved Polyethylene	Sodium Thiosulfate	24 hours
MS2 Bacteriophage	Autoclaved Polyethylene	Sodium Thiosulfate	24 hours
Polio 1 Virus	Autoclaved Polyethylene	Sodium Thiosulfate	24 hours
Physical			
Temperature	Measured On-site	None	Immediately
Particle Count	Polyethylene	None	Not specified
Total Suspended Solids	Polyethylene	None	7 days
Turbidity	Polyethylene	None	48 hours
UV_{254} Transmittance	Polyethylene	None	24 hours
Electrical Conductivity	Polyethylene	None	28 days
Total Dissolved Solids	Polyethylene	None	7 days
Chemical			
pH	Polyethylene	None	24 hours
Cations (Ca, K, Mg, Na)	Acid-washed Polyethylene	Nitric Acid	6 months
Alkalinity	Polyethylene	None	14 days
Chloride	Polyethylene	None	28 days
Sulfate	Polyethylene	None	28 days
Nitrate	Polyethylene	None	28 days
Chlorine Residual	Measured On-site	None	Immediately
Iron	Acid-washed Polyethylene	Nitric Acid	6 months
TOC	Amber Glass	None	28 days

Virus Seeding Methodology

Virus feed solution was spiked into the pipes ahead of the disinfection contactors using membrane feed pumps; the addition points were located side-by-side on separate pipes leading to the two contactors. The flow rate of the feed solution pump was verified twice prior to the experiment. The flow rate of wastewater during the experiment could not be controlled but was monitored several times: it was recorded at the beginning of the experiment, after completion of the chlorine contactor testing, and after the UV irradiation chamber testing. Feed pump flow rate was verified at the end of the experiment by dividing the volume of the solution fed by the duration of spiking.

A five gallon feed solution container was partially filled with non chlorinated filtered plant water. Stock MS2 bacterial virus and Polio virus solutions were added to the water in the container (Polio virus stock was defrosted prior to addition) and the contents were filled with plant water to the 5-gal mark. The contents were thoroughly mixed and the feed container effluent was attached to the suction side of the feed pump. The feed pump was turned on and the time was recorded. Three detention times of the pipe and the disinfection contactor were fed before samples were collected.

Sample Collection in the Chlorine Contactor

Downstream samples were collected first, starting at the location of the longest contact time to prevent contamination of the sampling apparatus and to avoid hydraulic disturbance upstream from the sampling location. Three 100-L containers were placed next to each sampling location and a sodium thiosulfate solution was poured into each container to dechlorinate collected sample. This allowed for collection of 300 L samples. Next, a submersible pump was immersed in the middle of the channel at the sampling location and the sample was pumped through the plastic hose into the sample containers. Chlorine residual in the contactor was measured simultaneously by collecting a small amount of water coming out of the hose.

MS2 virus samples were collected by submerging sampling bottles in the water collected in the sampling containers. Polio virus samples were collected in the field using a ten-inch Zetaplus Virusorb cartridge filter (CUNO catalog # 45144-01-1MDS) housed in a filter holder and filtered using a submersible pump. After the filtration was complete, 900 mL of sterile 3% beef extract (BBL catalog # 97531) , pH 9.5 was poured into the filter housing to cover the filter completely. This was allowed to sit for 5 minutes. After this time, the

filter housing was connected to a pressure vessel and the 3% beef extract was eluted off the filter and collected into a 1 liter plastic beaker. The pH was adjusted between 7.0 and 7.5 as quickly as possible with 1N hydrochloric acid (HCl). The volume was poured into 1 liter plastic bottles and shipped on ice to the laboratory for reconcentration and assay.

Sample Collection in the UV Irradiation Chamber

Downstream samples were collected first, starting at the location after the fifth UV bank. Seeded polio virus samples were filtered in the field using a ten-inch Zetaplus Virusorb cartridge filter (CUNO catalog # 45144-01-1MDS) housed in a filter holder and filtered using a submersible pump. The submersible pump was immersed in the middle of the channel at the sampling location and the sample was pumped through the filter. The volume of water pumped through the filter was determined by measuring it using a meter placed in the water line after the filter. Typically, 500 L of water was filtered for UV light-irradiated samples. After the filtration was complete, the samples were processed as described for the chlorine contactor.

The samples were collected after each UV bank as well as a sample before the first bank to determine the influent concentration. After collecting those samples, the UV lamps were turned off and after 10 minutes, Polio and MS2 virus control samples were collected.

Upon completion of the experiment, the sampling equipment was sterilized by filling the sampling containers, pumps, filter assemblies and hoses with chlorinated water.

BENCH-SCALE VIRUS SEEDING AND INACTIVATION EXPERIMENTS

Bench-Scale Chlorination Experiment

The bench-scale chlorination experiment was conducted in 3-L amber-glass reactor bottles. Polio virus was not evaluated in this experiment due to the appreciable chlorine demand exerted by the residual freon in the Polio virus stock.

A filtered wastewater sample was collected at the plant and delivered to the laboratory. The test was conducted the following day. Stock MS2 virus solution was added to the container filled with the wastewater and the contents were thoroughly mixed. Reactor bottles were filled with the spiked wastewater using a graduated cylinder. An aliquot of the concentrated sodium hypochlorite stock solution was added into the reactor bottle, the

- Subsequently, the probe was submerged half way deep into the channel and readings were taken next to the walls and in the middle of the channel.
- The probe was moved to the location after the fifth UV lamp bank and the measurements as taken ahead of the first bank were repeated. Readings were collected at each location every 1-2 seconds for 15 seconds.
- The readings of the probe in the channel crossection at the location ahead of the lamp banks and after the banks were compared to and determine whether tracer was distributed uniformly.
- The tracer feed pump was turned off and the decay at the end of the channel (after the fifth bank) was observed.

The second batch of the tracer was used to conduct the tracer test in conformance with the following protocol:

- The wastewater flow was verified before and after the experiment.
- After the conductance returned to background levels, the probe was positioned after the fifth lamp bank. The probe was placed in the middle of the channel and submerged to the middle of the channel depth.
- The tracer pump was turned on simultaneously with the stopwatch and the flow adjusted to 5 gpm. Conductance was recorded every 1-2 seconds until readings stabilized at a higher level due to tracer addition. The time when the first tracer appeared was noted.
- After the conductance reading stabilized, the stopwatch was zeroed and the tracer pump was turned off while simultaneously starting the stopwatch again. Conductance was recorded again every 1-2 seconds until the readings stabilized at the background level. This portion of the test (decaying conductance) was recommended as the best way to obtain full-scale tracer test results.

ANALYTICAL METHODOLOGY

Table 3-4 summarizes the standard analytical methods employed throughout this study. Each analytical method is described in more detail in the sections that follow.

TABLE 3-4

SUMMARY OF ANALYTICAL METHODS

Parameter	Method Reference
Microbiological	
Total Coliform Bacteria	Standard Methods 9221(B): MPN Method
Fecal Coliform Bacteria	Standard Methods 9221(E): MPN Method
Fecal Streptococci Bacteria	Standard Methods 9230: MPN Method
Enterococci Bacteria	Standard Methods 9230: MPN Method
Heterotrophic Plate Count	Standard Methods 9215: Pour Plate Method
MS2 Bacteriophage	Not Available - Double Agar Overlay Method
Physical	
Temperature	Standard Methods 2550B
Particle Count (1-120 µm)	Not Available
Total Suspended Solids	EPA 160.2
Turbidity	EPA 180.1
UV254 Transmittance	No Standard Method Available
Electrical Conductivity	EPA 120.1
Total Dissolved Solids	EPA 160.1
Chemical	
pH	EPA 150.1
Calcium	EPA 215.1: Flame Atomic Absorption
Magnesium	EPA 242.1: Flame Atomic Absorption
Potassium	EPA 258.1: Flame Atomic Absorption
Sodium	EPA 273.1: Flame Atomic Absorption
Alkalinity	EPA 310.1
Chloride	EPA 300.0: Ion Chromatography
Sulfate	EPA 300.0: Ion Chromatography
Nitrate-N	EPA 300.0: Ion Chromatography
Iron	EPA 200.7: Inductively Coupled Plasma
TOC	EPA 415.2
Disinfection By-products	
Volatile Organic Analysis	EPA 5030/524.2: Purge & Trap GC/MS
Volatile Organics (110-450 bp range)	Standard Methods 6040: Closed Loop Stripping GC/MS
Semi and Non-volatile Organics	Particle Beam LC/MS
Organics Screening	HPLC/UV
Peak Identification	High Resolution FAB GC/MS
Aldehydes	No Standard Method: GC/ECD
Whole Effluent Toxicity	
Chronic Fathead Larvae Survival and Growth	EPA/600/4-89-001
Chronic Ceriodaphnia Survival and Reproduction	EPA/600/4-89-001
Chronic Selanastrum Algae Growth Bioassay	EPA/600/4-89-001

Standard Methods = APHA,AWWA,WEF,"Standard Methods for the Examination of Water and Wastewater, 18th Edition," 1992

EPA = EMSL,"Methods for Chemical Analysis of Water and Wastes,"EPA-600/4-79-020, Revised March 1983

EPA = EMSL,"Methods for the Determination of Organic Compounds in Drinking Water,"EPA/600/4-88/039.

Bacterial Analysis

The multiple-tube fermentation technique, detailed in Standard Method 9221, was used to determine total and fecal coliform bacterial densities. The results were reported in terms of the most probable number (MPN) of coliform per 100 milliliters (mL) of sample. Five appropriate dilutions were employed for each sample and dilutions were reviewed and adjusted throughout the study as needed.

The multiple-tube fermentation technique, detailed in Standard Method 9230, was used to determine fecal streptococcus and enterococcus bacterial densities. The results were reported in terms of the most probable number (MPN) of coliform per 100 milliliters (mL) of sample. Five appropriate dilutions were employed for each sample and dilutions were reviewed and adjusted throughout the study as needed.

The pour plate technique, detailed in Standard Method 9215B, was used to determine heterotrophic plate counts.

All sample bottles used for collecting samples from the chorine contactor and UV contactor for microbial assay contained 1 mL of a 1% sodium thiosulfate solution, which was added to neutralize the chlorine residual and prevent any further disinfection.

MS-2 Bacteriophage Analysis

The bacteriophage assay is derived from the agar overlay technique described by Adams, (1959). A suspension of the *E. coli* host was prepared 6 hours prior to each phage assay. Three mL of sterile TYE consisting of 8.0 g/L TYE broth were added to an agar slant containing the *E. coli* host. The TYE was pipeted up and down to suspend the bacteria from the slant into the broth. One mL of the suspension was then added to a sterile 500 mL flask containing 100 mL of sterile TYE. One mL of 0.1 M calcium chloride was added, and the flask was placed in a shaking water bath at 37°C. The bacteria were agitated at 37°C for 5 to 6 hours and poured into sterile eyedropper hottles. The host bacteria were either used immediately for the phage assay, or placed in cold storage at 4°C for up to 24 hours until needed.

The bacteriophage enumeration procedure requires that the phage containing sample and the *E. coli* host be mixed in a soft 'top' agar which is then poured over the surface of a hard

'bottom' agar contained in a petri dish. Soft top agars were prepared by mixing 8.0 g/L of TYE broth and 7.0 g/L of agar (Difco, Bacto^{TM} Agar, 0140-01 GB) in deionized water. The mixture was brought to a boil and transferred into 13x100 mm culture tubes in 2.5 mL aliquots. The tubes were capped and autoclaved for 20 minutes at 121^{o}C. After sterilization, the tubes were placed in cold storage at 4^{o}C until needed. Hard top agars, which were sometimes required during the phage assay were prepared in a manner identical to the soft top agars, except that 15 g/L of agar instead of 7.0 g/L were added to the TYE broth.

Hard bottom agars were prepared in advance of the phage assay by mixing 8.0 g/L of TYE broth and 15.0 g/L of agar in deionized water in a 2 L Erlenmeyer flask. The mixture was boiled, capped with a foam plug, sealed with aluminum foil and autoclave tape and autoclaved for 20 minutes at 121^{o}C. After the sterile mixture had cooled to approximately 55^{o}C, ten mL aliquots were dispensed into presterilized petri dishes, and the covers placed loosely over the top of each dish to allow moisture to escape. After the hard agar solidified in the petri dishes, they were closed, inverted, and stored at 4^{o}C until needed.

Samples were diluted using a serial dilution scheme. Dilutions were made in prepared tubes containing sterile phosphate buffered saline (PBS) at pH 7.2. The PBS was composed of 0.55 g/L of dibasic sodium phosphate (NaH_2PO_4), 2.98 g/L of monobasic sodium phosphate (Na_2HPO4), and 8.5 g/L of sodium chloride (NaCl) in deionized water. After dissolving the buffer reagents, the mixture was dispensed into 16x125 mm screw-capped culture tubes in 9.0 or 9.9 mL portions. The tubes were capped and autoclaved for 20 minutes at 121^{o}C and placed in cold storage at 4^{o}C until needed.

Samples were diluted so that when the samples were enumerated, the number of plaques per dish was in the range of 30 to 300 plaque forming units (PFU). Ten-fold dilutions were performed by adding 1.0 mL of sample to 9.0 mL of sterile PBS. This tube was vortexed and the procedure repeated in a serial fashion until the desired dilutions were achieved. When required, 100-fold dilutions were made by adding 0.1 mL of sample to 9.9 mL of PBS.

After all sample dilutions were prepared, 0.1 mL of the appropriate sample dilution tube was added to a soft top agar, which was maintained at 45 to 47^{o}C in a heated dry block. Approximately 0.2 mL (two drops=0.1mL) of the previously prepared *E. coli* host suspension was aseptically added to the soft agar tube using an eyedropper. The tube was

gently mixed to disperse the phage and host evenly throughout the tube. The contents of the tube were then poured over the bottom-agar-containing petri dish. After the soft agar solidified (usually less than 10 minutes), the petri dish was inverted and placed in an incubator at 37°C for 18 to 24 hours. Each sample dilution was plated in duplicate, and for each sample, three or four dilutions were plated. Petri dishes were labeled to identify the run number and sample dilution. After 18 to 24 hours, the petri dishes were removed from the incubator and examined for the presence of plaques (clearings in the bacterial lawn). Plates containing less than 300 PFU were counted using a colony counter. The total number of plaques counted on any petri dish was used in combination with the dilution factor for that petri dish to determine the phage density in the original sample.

Quality control in the maintenance of the *E. coli* cultures was established by weekly propagation of the culture from one set of agar slants to fresh agars slants. For long-term maintenance, the host culture was grown for 6 hours, pelleted by centrifugation and resuspended in 20% sterile glycerol. This was dispensed in 1.0 mL aliquots and stored at 0°C. Once a month, fresh agar slants were prepared with this frozen stock. Quality control in the maintenance of the phage-host system was evaluated during each phage assay by plating samples from the diluted stock virus. Purity of the *E. coli* host during any particular phage assay was evaluated by plating 1 mL of the host suspension with no virus added. Contamination of the host suspension by the phage is apparent by the formation of plaques on control petri dishes.

Poliovirus Analysis

The beef extract containing the field filtered virus was placed in a 1 L beaker. The pH was adjusted to 3.5 with 1N HCl and the sample was stirred for 15 minutes and then centrifuged at 3000 g for 30 minutes. After centrifugation was complete, the supernatant was discarded and the pellet was resuspended in 25 mL of prewarmed 0.1M sodium phosphate dibasic anhydrous ($NaHPO_4$). The pH was adjusted to 7.2 to 7.3 with 1N HCl and the solution was stirred for 5 minutes. The sample was placed in a sterile 50 mL centrifuge tube and 10 mL of freon was added. This was mixed well for 10 minutes and centrifuged at 3000 g for 15 minutes. After centrifugation, the top layer was carefully removed using a sterile pipette so as not to disturb the freon layer or the interface. 0.5 mL of mycostatin, penicillin/streptomycin, kanamycin and gentamicin was added to the sample and incubated in a 37°C water bath for 30 minutes. The sample was dispensed in 20 mL vials, labeled and stored at -80°C until the assay was performed.

BGM cells were grown in 5% fetal calf serum Eagles MEM at 37°C in a carbon dioxide (CO_2) incubator for 5 days. The cells were ready to be assayed when a confluent monolayer was observed. A 10-fold dilution of the virus stock or sample was made by adding 0.3 mL of virus stock or sample to 2.7 mL tris buffer solution. The cell monolayer was washed with prewarmed tris buffer solution. For each sample, three dilutions were plated in triplicate and a negative control was performed using 0.3 mL for wells or 3.0 mL for flasks of tris buffered saline solution. 0.3 mL of each dilution was added to each well in a 6 well tray. 3 mL of sample was added to each flask when assaying a larger volume of sample. The well trays and/or flasks were incubated at 37°C for 45 minutes in a CO_2 incubator. The sample was rocked every 15 minutes to prevent drying of the cells. The overlayer media was prepared by melting 100 mL of 1% agar in a steam bath. 2 mL of sodium bicarbonate ($NaHCO_3$) and 6 mL Hepes was added to 100 mL of 2X Eagle's minimal essential media (MEM), mixed and the pH was adjusted to 7.1 to 7.4 with 1N HCl. 2 mL of glutamine, 4 mL of fetal bovine serum and 0.5 mL of mycostatin, kanamycin and penicillin/streptomycin was added to the MEM solution and 100 mL of 1% agar was added to the MEM solution and allowed to cool. 3 mL of overlayer agar was pipeted into each well of a 6 well tray and 20 mL of overlayer agar was pipeted into each flask. The agar was solidified and each well and/or flask was incubated at 37°C for 48 hours in a CO_2 incubator. After 48 hours, the agar overlay was removed and stained with crystal violet. Plaques were counted and the titer was determined.

Particle Counting

Particle counting was conducted on the filtered secondary effluent. Particle counting was performed using a Met one Series 9000 particle enumeration software and hardware along with the Model 250 batch sampler and Model 211 laser diode. The Model 211 is a laser diode based sensor enumerating particles in the size range 1-120 µm. The sensor was calibrated to operate at a flow rate of 100 mL/min. The coincidence limit of this sensor is 3,500 particles per mL, which applies to all particles within the counting range of the sensor, even if the channels are not set to count within the full range. According to the manufacturer's information, the coincidence error at counts below the concentration limit is less than 10 percent. The instrument was calibrated by Met One prior to collection of particle count data. Calibrated monosized polymer microspheres (Duke Scientific Corporation, Palo Alto, California) were used for the verification in sizes of 2, 4, 10, 20 and 30 µm. The manufacturer's calibration was verified at the beginning of the study and

near the end of the project. Calibration verification tests conducted on August 26, 1993 using the same monospheres showed peaks at the same particle sizes as the first test, indicating particle counter calibration did not vary during the course of the study.

The particle counter was rinsed with approximately 100 mL of clean water and a clean water sample was run to insure the sample cell was clean prior to sample analysis. At least 200 mL of each water sample to be counted was collected in the appropriate beaker. After placing the particle beaker in the pressure chamber, the sensor was rinsed with 50 to 100 mL of the sample to be counted, and three counts were made of each sample. Data from the three counts were averaged, with the average value being reported as the count for that sample. Samples were not stirred between replicate counts. Because of the small number of larger size particles and the short duration of particle sampling (approximately 1 minute), it was not necessary to use a magnetic stir bar to keep particles suspended.

Disinfection By-Products

Sample Preparation for HPLC Screening and Mass Spectral Analysis. One liter or 500 mL of the filtered secondary effluent samples (preceding and following disinfection) were lyophilized to less than 20 mL and redissolved in high performance liquid chromatography (HPLC) purity water (Fisher Scientific, Santa Clara, CA) to a final volume of 20 to 40 mL. A different concentration method utilizing solid-phase extraction with Mega Bond Elut C_{18} sorbent (Varian, Harbor City, CA) was also utilized for the second UV sample collected in June, 1993. This concentration method consisted of loading up to 3 liters of sample per column onto individual Mega Bond Elut Columns which were pre-equilibrated with HPLC grade water. The adsorbed material was then sequentially eluted from the C_{18} columns using acetonitrile (ACN) in aqueous trifluoroacetic acid (TFA) as follows: 25 % ACN in 0.1 % TFA, then 40 % ACN in 0.1 % TFA, and finally 95 % ACN in 0.05 % TFA. This last eluant was prepared for analysis by concentrating to near dryness by roto-evaporation in order to remove the organic solvent. Redissolved samples were centrifuged (1,500 rpm, 5 min) to remove undissolved salts and particulates. Half of the concentrates were set aside for direct HPLC analysis. The other half of the concentrates and the centrifugation pellets were acidified to pH 2.3 with 1 M HCl and extracted with ethyl acetate. Three successive partitionings with an equal volume of ethyl acetate were performed on each sample. The combined successive extracts were

roto-evaporated to dryness in pear flasks and then dissolved in 0.1 mL of acetonitrile followed by 3.9 mL of HPLC grade water.

Peak Identification. The concentrates were analyzed with a Perkin Elmer Series 410 HPLC equipped with a 5 mL sample loop and reversed phase C_{18} column. The following mobile phase solvent program was used with a 1.0 mL/min flow rate (linear gradient): 95% HPLC grade water, 0% ACN and 5% TFA for 10 min.; 0% HPLC grade water, 95% ACN, and 5% TFA for 105 min.; 0% HPLC grade water, 95% ACN, and 5% TFA for 5 min.; and 0% HPLC grade water, 100% ACN and 0% TFA for 5 min. UV absorbance was monitored at 220 and 280 nm using a Perkin Elmer Diode-Array Detector (Model LC 235). Attenuation was set at 0.5 ahsorhance units full scale (AUFS). Additional resolution of the polar C18 solvent front material was obtained by using a Dionex PAX-500 column #3095 (mixed function - C18 anion-exchange) and a Dionex PCX-500 column #1321(mixed function - C18 and cation exchange). UV absorbance was monitored at 220 nm with an attenuation of 2.0 AUFS. Fraction collection of nonpolar peaks that were present only in the disinfected samples were analyzed by fast atom bombardment mass spectrometry (FAB/MS) to obtain preliminary compound identifications. The FAB/MS analysis was performed by Mass Search, Inc. (Modesto, CA) using a VGZAB-2SE analyzer (VG Quadrapole, UK) with a VG11250 data package and liquid matrix selected ion monitoring (LM/SIM) for high resolution. High energy cesium was used for FAB with meta-nitrobenzyl alcohol as the matrix.

Analysis of volatile compounds was also performed by purge and trap (EPA Method 5030) prior to analysis by GC/MS (EPA Method 8260) for the regulated and unregulated Safe Drinking Water Act target compound list and by closed loop stripping (Standard Method 6040) prior to analysis by GC/MS. GC/MS identification of non target peaks was attempted by mass spectra library search and quantitation obtained from the relative response of the closest surrogate standard. Analysis of less thermally stable semi-volatile and nonvolatile compounds was also performed by EPA Method 625 extraction and solvent exchange to acetonitrile prior to particle beam LC/MS. An acetonitrile/water gradient was used with elution conditions intermediate between optimum conditions for separation of PNA and phenolic compounds. Quantitation was performed for all peak areas at least 10% of the peak area of the closest surrogate standard.

TESTING MATRIX

Testing matrices detailing the specific parameters analyzed for each experiment is presented in Table 3-5 for the bench-scale experiments and Table 3-6 for the full-scale experiments.

TABLE 3-5
EXPERIMENTAL BENCH-SCALE TESTING MATRIX

Run Date	1 10/6/92	2 11/3/92	3 11/24/92	4 12/15/92	5 12/22/93	6 1/4/93	7 1/7/93	8 1/11/93	9 1/19/93	10 3/2/93	11 5/4/93	12 6/16/93	13 7/15/93	14 8/4/93	15 8/24/93	Total
UV testing																
Doses + Control	6+1	6+1				6+1		6+1	6+1	6+1	6+1		6+1	6+1	2+1	10
Photoreactivation																0
UV Calibration			BS	CB	CB		BS									4
Chlorine testing																
Doses + Control		6+1				6+1		6+1	6+1		2+1					5
Kinetics + Control										2+1	2+1		2+1	2+1	2+1	5
Target Microorganisms																
HPC		√				√		√	√				√	√	√	7
Total Coliforms	√	√				√		√	√	√	√		√	√	√	10
Fecal Coliforms	√	√				√		√	√	√	√		√	√	√	10
Fecal Streptococci	√	√				√		√	√							5
Enterococci	√	√				√		√	√							5
MS2 Phage		√	√	√	√	√	√	√	√	√	√		√	√	√	13
Polio										√	√		√	√	√	5
By-Products Evaluation																
DBPs									√		√	√			√	4

BS = Bench scale apparatus calibration
CB = Collimated beam experiment
√ = indicates experiments being performed

TABLE 3-6

EXPERIMENTAL FULL-SCALE TESTING MATRIX

Run Date	1 2/10/93	2 2/25/93	3 3/11/93	4 3/24/93	5 4/28/93	6 5/13/93	7 5/19/93	8 5/26/93	9 6/2/93	10 6/9/93	11 6/16/93	12 6/23/93	13 6/29/93	14 7/7/93	15 7/13/93	16 7/20/93	17 7/27/93	18 8/3/93	19 9/14/93	20 9/23/93	21 9/29/93	22 11/10/93	23 12/6/93	Total
UV testing																								
Samples	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5		22
Controls									MS2	TC/FC	MS2	FS/E	TC/FC	Polio	FS/E	TC/FC	FS/E	MS2	MS/Pol	MS/Pol.	MS/Pol			13
Photoreactivation																							√	1
Chlorine testing																								
Samples	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5	1+5			21
Controls									MS2	TC/FC	MS2	FS/E	TC/FC	Polio	FS/E	TC/FC	FS/E	MS2	MS/Pol.	MS/Pol.	MS/Pol			13
Target Microorganisms																								
HPC	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√			21
Total Coliforms	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	23
Fecal Coliforms	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	23
Fecal Streptococci	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√			21
Enterococci	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√			21
Seeding																								
MS2 Phage									√		√			√				√	√	√	√			7
Polio 1														√				√	√	√	√			5
Indigeneous Virus														√				√						2
By-Products and Toxicity Evaluation																								
DBPs																						√		1
Toxicity																						√		1
Title 22 Compliance																								
10 days																						√		1

1+5 = one feed and five samples along the contactor
MS2 = MS2 Bacteriophage
TC/FC = Total Coliforms and Fecal Coliforms
FS/E = Fecal Streptococci and Enterococci
√ = indicates experiments being performed
Indigeneous Virus = Polio, MS2

Section 4

MONTGOMERY WATSON

SECTION 4

WATER QUALITY CHARACTERISTICS

This section presents a summary of the water quality characteristics of the filtered secondary effluent produced by the EVMWD Regional Reclamation Facility. The effectiveness of chlorine and UV disinfection is known to depend upon several water quality parameters. Chlorine disinfection is principally affected by the wastewater pH,. the concentrations of ammonia, TOC, and chemical substances exerting a "chlorine demand", and the presence of particles. UV disinfection is principally affected by the UV_{254} transmittance of the wastewater and the presence of particles or chemicals substances which can interfere with the transmission of the UV light. Particles interfere with the transmission of UV light by causing UV light scattering or UV light absorption which can effectively shield microorganisms from the germicidal effects of the UV light. Many studies have been performed to try to correlate fluctuations in UV_{254} transmittance of a wastewater with variations in measurements of particle density such as turbidity, TSS, and particle counts. The variation in turbidity, TSS, and total particle counts observed for the EVMWD effluent over the 12 month study period were too small to demonstrate any meaningful correlation with the UV_{254} transmittance.

VARIATIONS IN WATER QUALITY DURING THE STUDY

This section presents an examination of the variations in the water quality parameters that would have affected UV disinfection performance during the 12 month testing period. These parameters include UV_{254} transmittance, turbidity, TSS, particle counts, and bacterial densities. Protocols for each analysis were presented in Chapter 3 of this report. Water quality parameters were measured each time bench-scale or full-scale experiments were conducted. During the 12 month study period, one to five measurements were made each month. The data does not provide a detailed examination of diurnal or daily variation, but does present the range of values that can be expected throughout the year.

UV_{254} Transmittance

Figure 4-1 presents a time-series plot of the values of UV254 transmittance measured in the filtered secondary effluent during the testing period from October 1992 through September 1993. From the data presented in Table 4-1, a 3.3 % relative standard deviation (RSD) was observed in the UV254 transmittance values with a mean of 76 % for 28 samples collected during a 12 month period. The minimum UV_{254} transmittance value was 70 % and the maximum UV_{254} transmittance value was 80 %.

TSS

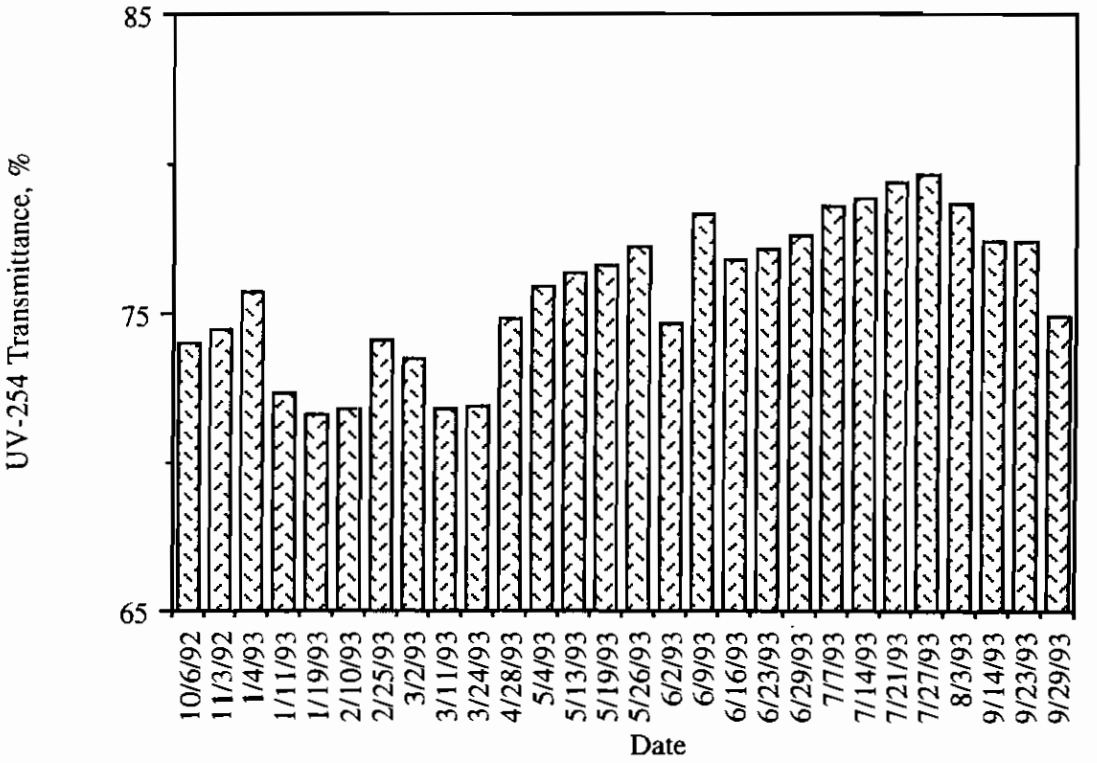
Figure 4-2 presents the TSS values measured in the filtered secondary effluent during the testing period. The majority of the TSS values fell below the method reporting limit. From the data presented in Table 4-1, a minimum value of 1.5 mg/L and a maximum value of 7.0 mg/L was observed during the testing period. Calculation of the mean and % RSD was not possible due to the large number of "less than" values reported for this parameter.

Turbidity

Figure 4-3 presents the turbidity values measured in the filtered secondary effluent during the testing period. From the data presented in table 4-1, a 33 % RSD was observed in the turbidity values with a mean of 0.6 NTU for 28 samples collected during a 12 month period.

Particle Counts

Figure 4-4 illustrates the variations in the total number of particles present in the filtered secondary effluent during the testing period. The total number of particles was determined as the sum of the particle counts from the six discrete size ranges. The protocol for particle counting was described in Chapter 3. The minimum total number of particles was 746 per mL and the maximum total number of particles was 5,300.



UV-254 TRANSMITTANCE AS A FUNCTION OF TIME FOR THE EVMUD FILTERED SECONDARY EFFLUENT

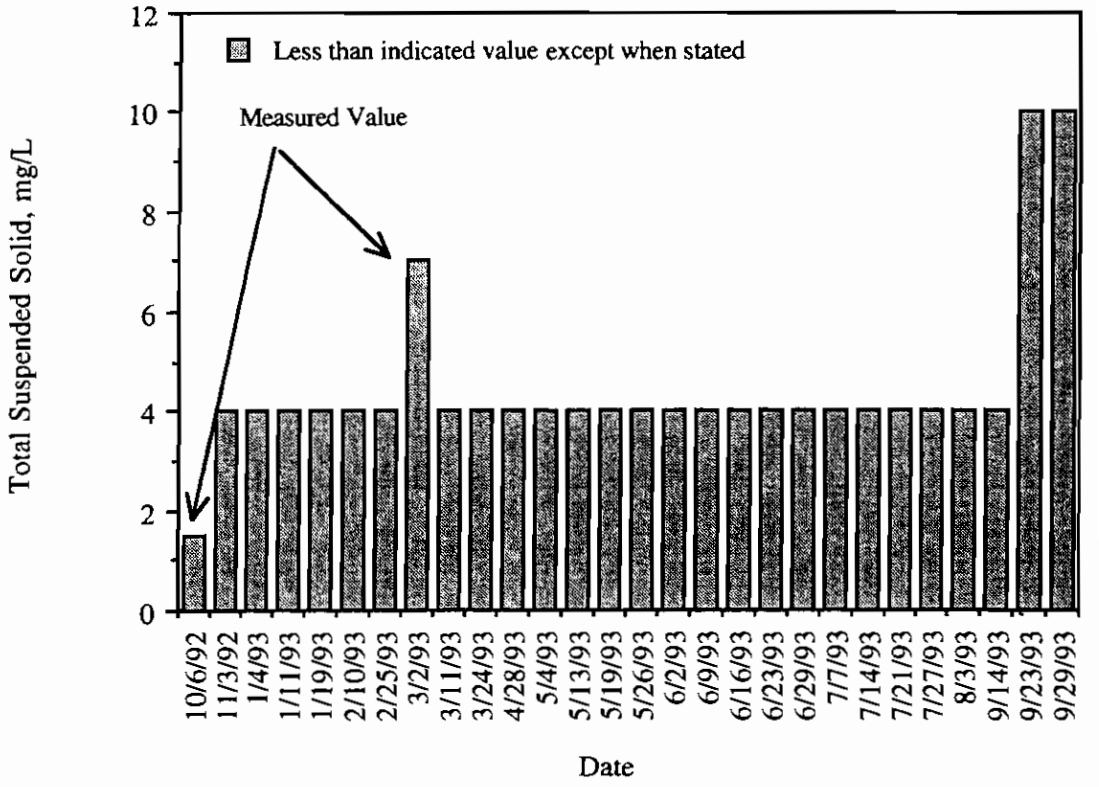
FIGURE 4-1

TABLE 4-1

SUMMARY OF WATER QUALITY PARAMETERS MEASURED FOR THE EVMWD FILTERED SECONDARY EFFLUENT

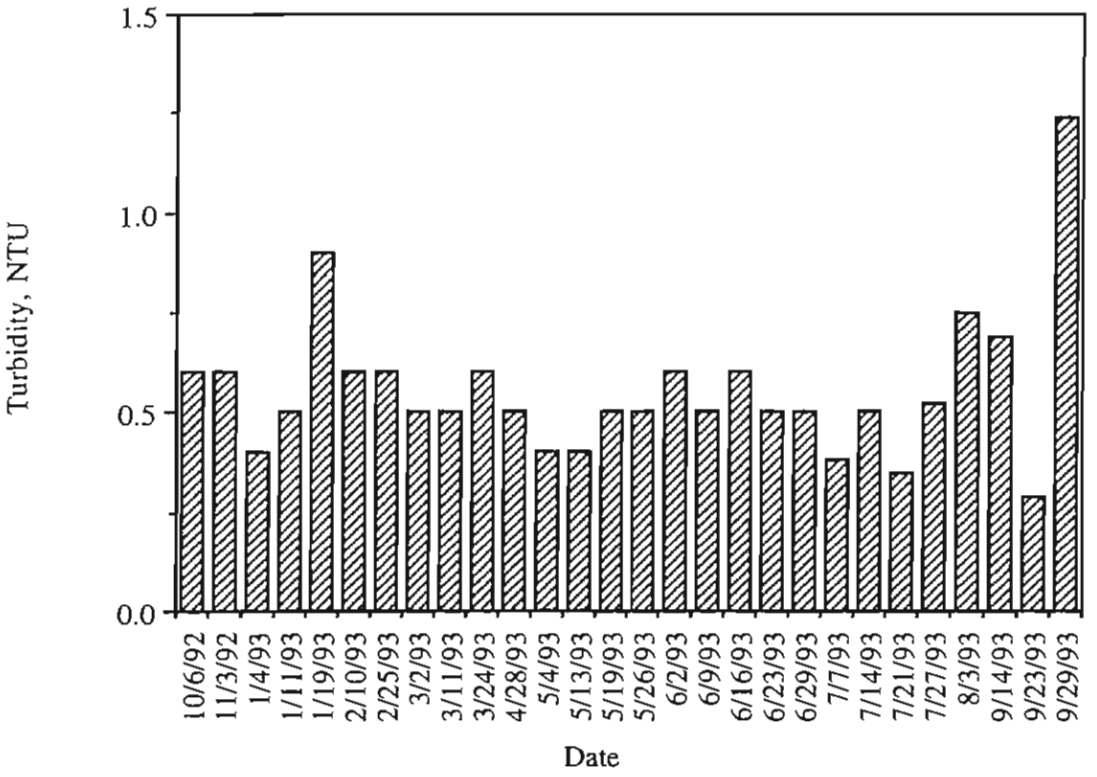
Parameters	Units Testing	n		Mean*	%RSD
Inorganic Analyses					
Temperature*	°C	27		24.2	13.1
pH		28		7.8	1.8
Alkalinity	mg/L	27		171	12.8
Turbidity	ntu	28		0.6	33.0
Particle Density (1-120 µm)	#/mL	28		2,495 *	NA
TSS	mg/L	28	<	4.4	NA
TDS	mg/L	28		823	14.3
Sodium	mg/L	27		166	12.1
Chloride	mg/L	27		167	16.9
Sulfate	mg/L	27		250	17.8
Calcium	mg/L	27		74	15.1
Nitrate-N	mg/L	27		10	28.9
Potassium	mg/L	27		10.8	15.8
Magnesium	mg/L	27		27	17.8
Iron	mg/L	27	<	0.1	0.0
Organic Analyses					
TOC	mg/L	28		5.4	12.3
UV-254		28		0.121	11.6
UV-254 Transmittance	%	28		75.8	3.3
Bacterial Analyses (Indigeneous Organisms)					
HPC	cfu/mL	21		4.6 E+4 *	NA
Total Coliform	MPN/100 mL	27		6.0 E+4 *	NA
Fecal Coliform	MPN/100 mL	27		2.1 E+4 *	NA
Fecal Streptococci	MPN/100 mL	26		1.3 E+3 *	NA
Enterococci	MPN/100 mL	26		7.2 E+2 *	NA

NA= Not Applicable
* Geometric mean
n Number of samples
% RSD Relative standard deviation
< indicates less than minimum reporting level



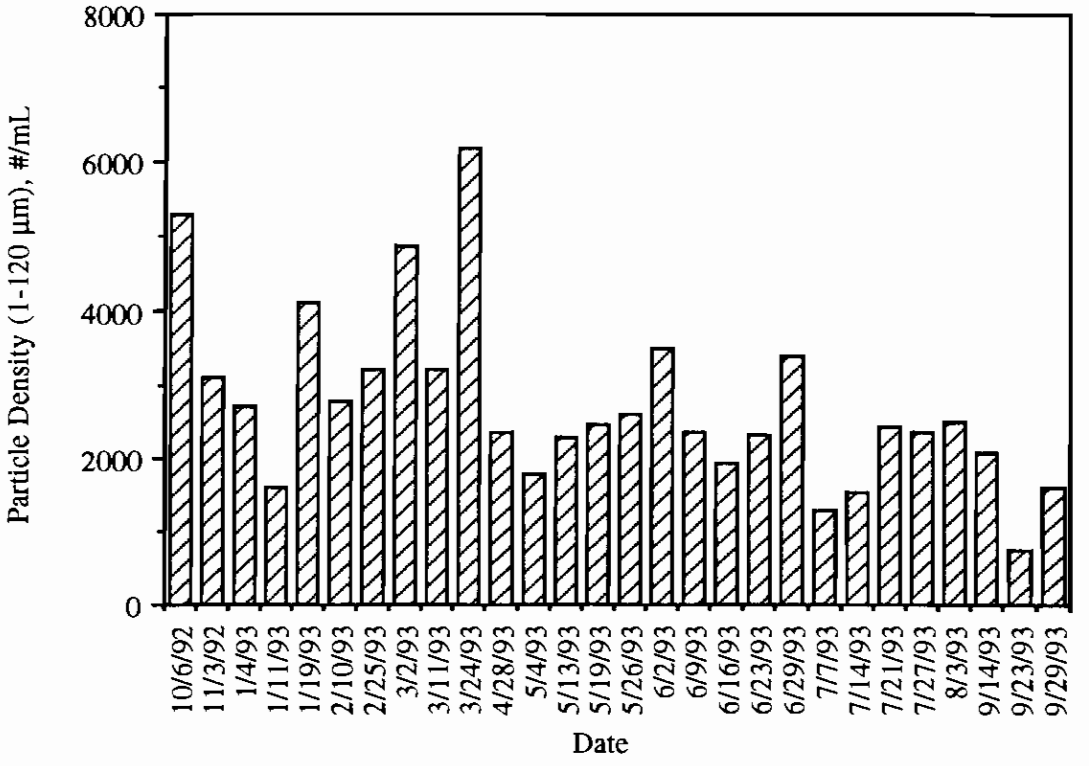
TOTAL SUSPENDED SOLID AS A FUNCTION OF TIME FOR THE EVMWD FILTERED SECONDARY EFFLUENT

FIGURE 4-2



TURBIDITY AS A FUNCTION OF TIME FOR THE EVMWD FILTERED SECONDARY EFFLUENT

FIGURE 4-3



PARTICLE COUNT AS A FUNCTION OF TIME FOR THE EVMWD FILTERED SECONDARY EFFLUENT

FIGURE 4-4

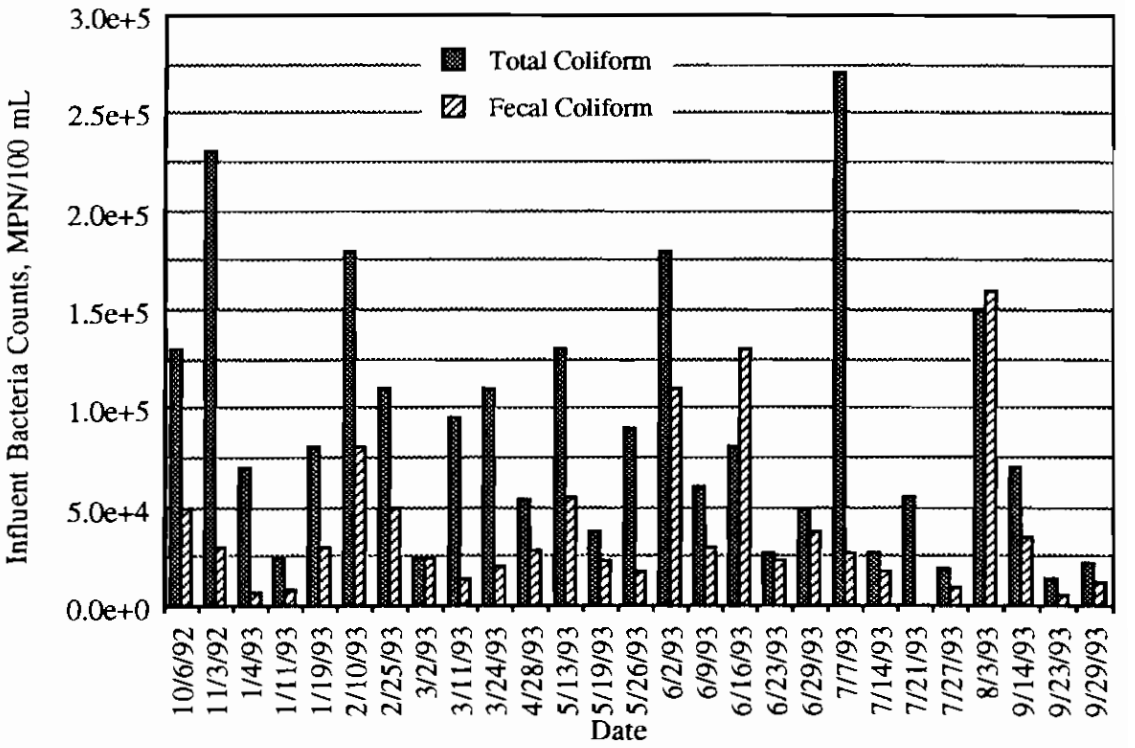
Bacterial Densities

Figures 4-5, 4-6 and 4-7 illustrate the densities of bacterial indicator organisms in the filtered secondary effluent during the testing period. The densities enumerated for each of these indicator groups varied by as much as one log during the testing period.

SUMMARY

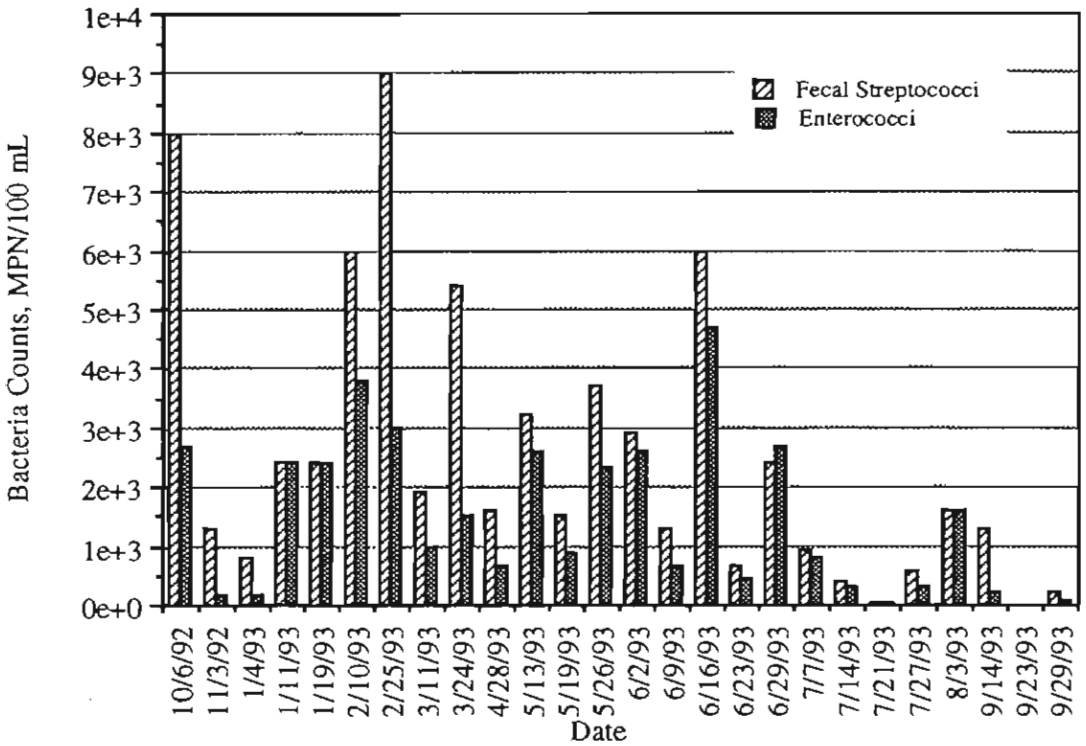
This section provided an evaluation of the variations in the water quality characteristics of the EVMWD filtered secondary effluent during the study testing period. The plant produces a high quality effluent well suited for UV disinfection. A sufficient amount of UV_{254} data was collected during the study period to allow EVMWD to utilize 70% transmittance in the calculation of their minimum required design dose.

The variation in measured turbidity, TSS, and total particle counts were too small to demonstrate any meaningful correlation with the UV_{254} transmittance values or the influent bacterial densities. The lowest UV_{254} transmittance values were measured during the winter (approximately January through March) and the highest values were measured during the summer (approximately June through September). The periods of low and high UV_{254} transmittance values did not show any correlation with the influent bacterial densities which showed a continuous variation by as much as one log throughout the year.



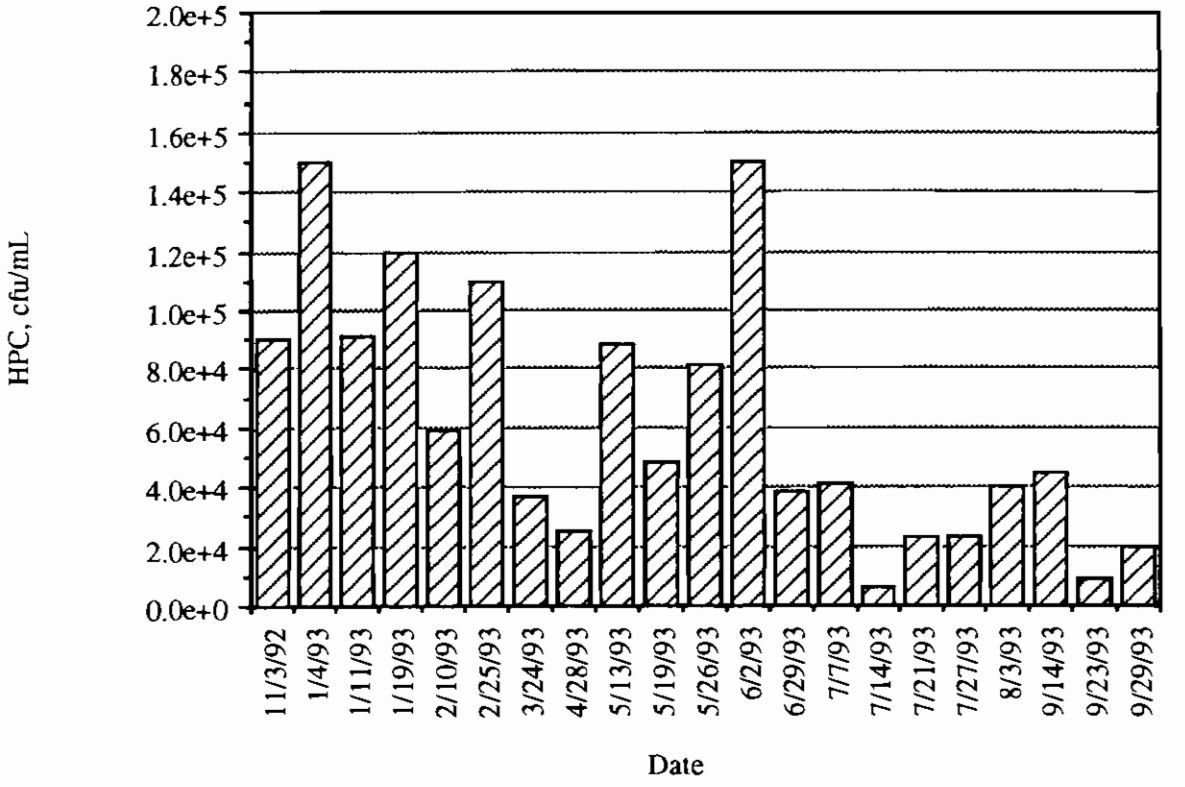
BACTERIA COUNTS AS A FUNCTION OF TIME FOR THE EVMWD FILTERED SECONDARY EFFLUENT

FIGURE 4-5



BACTERIA COUNTS AS A FUNCTION OF TIME FOR THE EVMWD FILTERED SECONDARY EFFLUENT

FIGURE 4-6



HETEROTROPHIC PLATE COUNT AS A FUNCTION OF TIME FOR THE EVMWD FILTERED SECONDARY EFFLUENT

FIGURE 4-7

Section 5

MONTGOMERY WATSON

SECTION 5

BACTERIA INACTIVATION RESULTS AND DISCUSSION

A critical objective of this study was to evaluate and define the minimum dose of chlorine or UV disinfectant required to meet the most restrictive total coliform requirement of the California Wastewater Reclamation Criteria and obtain either 4-log or complete inactivation of a target list of bacterial indicator organisms. These requisite doses also defined the minimum dose of each disinfectant to consider in investigating the disinfection byproducts and bioassay toxicity of the disinfected effluents. The minimum UV dose was also utilized to estimate the minimum lamp cleaning frequency for the full-scale system.

The doses required to inactive indigenous populations of total coliform, fecal coliform, *enterococci, fecal streptococci,* and heterotrophic plate count were determined from side-by-side UV and chlorine disinfection studies performed at bench-scale and at full-scale. By performing side-by-side testing, differences in the required dose for the two disinfectants would not be affected by differences in water quality. The bench-scale studies were performed in order to maintain flexibility in the applied doses and contact time and to see if the bench-scale data could reliably predict full-scale plant performance.

A total of five side-by-side UV and chlorine bench-scale tests were performed between October, 1992 and January, 1993 using filtered secondary effluent collected from the EVMWD Regional Plant less than 24 hours prior to initiation of the experiments. The chlorine disinfection studies were based on varying chlorine dose for a constant 2-hour contact time. Two additional chlorine kinetic bench-scale tests were performed in August, 1993. Full-scale testing was performed between the months of February, 1993 and September, 1993. The water quality during the bench-scale and full-scale testing was similar. The UV_{254} transmittance ranged from 72% to 79%, turbidity ranged from 0.3 to 1.2 NTU, TSS ranged from <4.0 to <10.0 mg/L, and the pH ranged from 7.2 to 7.9 units. The 2-hour chlorine demand was approximately 3 mg/L. The treatment plant provides full nitrification and partial denitrification so the ammonia levels were always expected to be less than 0.1 mg/L throughout the study.

CHLORINE DISINFECTION RESULTS

The log inactivation of indigenous total coliform, fecal coliform, enterococci, fecal streptococci, and heterotrophic plate count by chlorine disinfection were measured at bench-scale two different ways. Initially, only the applied chlorine dose was varied and a 2- hour contact time was used for all doses. This was done in order to mimic the full-scale plant requirement for a 2 hour detention time within the chlorine contactor. These experiments cannot reliably estimate the smallest chlorine dose and contact time (Ct value) required to achieve a defined level of inactivation because of the large chlorine depletion that occurred during the 2-hour contact time. Subsequent chlorine kinetic experiments were performed to obtain inactivation data at several shorter contact times for four different chlorine doses. These experiments provide a better estimate of the smallest Ct value required to obtain 4-log inactivation of the target organisms and total coliform values ≤2.2 MPN/100 mL.

Chlorine Disinfection Results Obtained from Bench-Scale Experiments

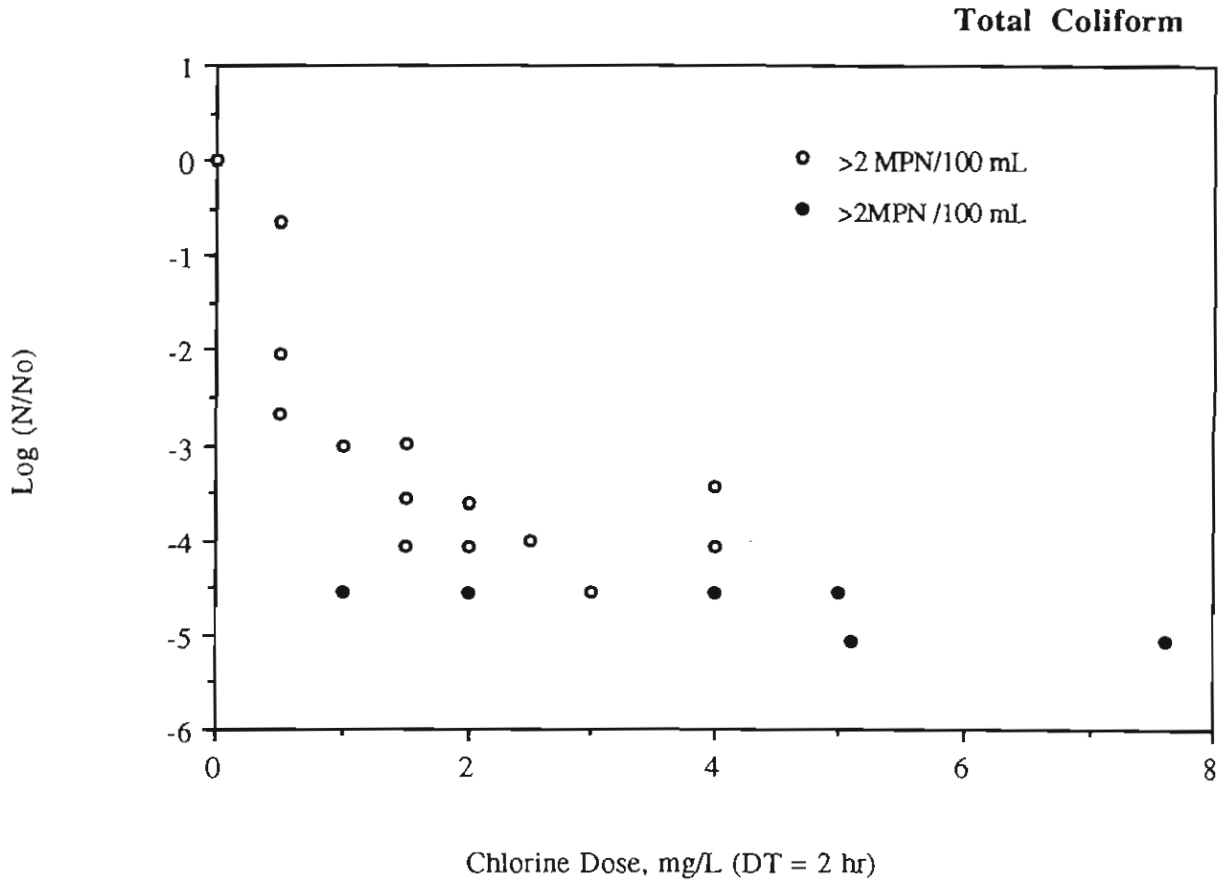
The chlorine dose required to achieve complete inactivation of all target organisms and total coliform densities <2.2 MPN/100 mL for the 2-hour contact time bench-scale experiments are presented in Table 5-1 for the 5 target bacterial indicator groups. Due to the large 2-hour chlorine depletion, free residual chlorine was only present for the higher applied chlorine doses which usually resulted in complete inactivation of the target organism groups. This data provide only a conservative estimate of the minimum chlorine dose required to meet the inactivation of the target organisms for a 2-hour contact time. Chlorine doses within the range of 1.5 to 5.1 mg/L were effective in reducing the total coliform density to ≤2.2 MPN/100 mL and completely inactivating all the other target organisms with the exception of heterotrophic plate count. At these chlorine doses, the heterotrophic plate count density ranged from 0.6 to 2.9 logs. Figure 5-1 summarizes the chlorine dose needed to consistently achieve complete inactivation of each target organism for all of the bench-scale experiments performed at a 2-hour contact time. A dose of 5 mg/L/L is needed to achieve ≤2.2 total coliform per 100 mL. As demonstrated in Figure 5-2, at this minimum chlorine dose, at least 3.0 log removal of heterotrophic plate count is achieved.

Two chlorine kinetic experiments, were performed to try to define the smallest Ct values to achieve complete inactivation of the target organisms. Inactivation data from these experiments were collected for total coliform, fecal coliform, and heterotrophic plate count

TABLE 5-1

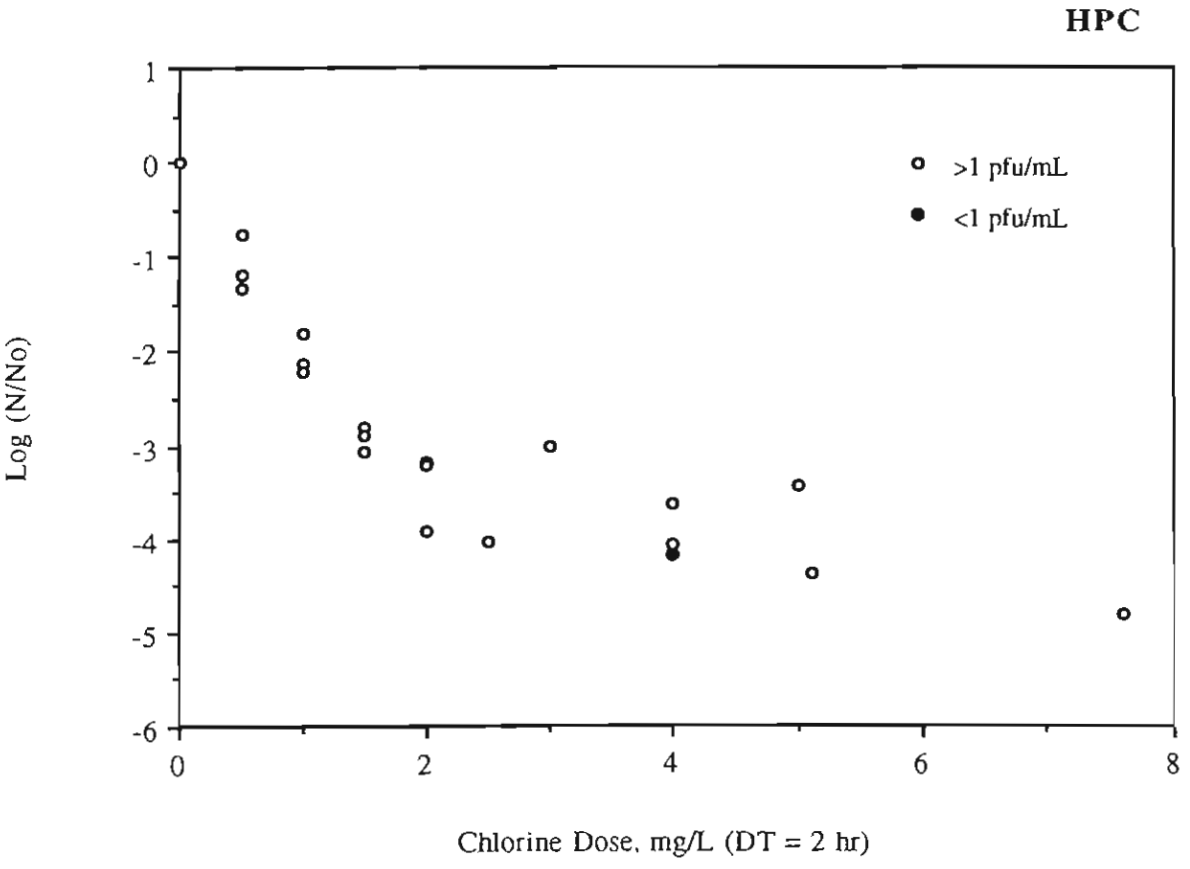
CHLORINE DOSE REQUIRED TO INACTIVATE TARGET BACTERIA BELOW DETECTION LIMITS IN BENCH-SCALE SYSTEM BASED ON 2 HOUR CONTACT TIME

Microorganism	Chlorine Dose mg/L
Total Coliform	5.0
Fecal Coliform	2.0
Fecal Streptococci	2.0
Enterococci	2.0
Hetertrophic Place Count	>7.6 mg/L



BENCH-SCALE INACTIVATION OF TOTAL COLIFORM BACTERIA AS A FUNCTION OF CHLORINE DOSE

FIGURE 5-1



BENCH-SCALE INACTIVATION OF HPC AS A FUNCTION OF CHLORINE DOSE

FIGURE 5-2

and are summarized in Table 5-2. These experiments indicate that a Ct value ≤ 21 *mg/L•min* is required to completely inactivate the total and fecal coliform. At a Ct value of 21 mg/L•min, heterotrophic plate count are still measured at a density of approximately 1.2 logs. Inactivation below detection limit for the heterotrophic plate count is not achieved even at a Ct values of 57 mg/L•min based on the kinetic experiments or a Ct value of 150 mg/L•min based on the 2-hour contact time experiments.

Chlorination Disinfection Results Obtained From Full-Scale Experiments

The log inactivation at full-scale was assessed by analyzing the free chlorine concentrations and microbial densities of samples collected from several locations within the chlorine contactor. Contact times and Ct values for each sampling location were calculated in accordance with the equations provided in Table 5-3. Only a conservative estimate of the smallest Ct value required to consistently achieve inactivation of the target bacteria can be estimated from this data. This is due to the fact that the selected sampling locations were not close enough to provide short enough contact times to accurately determine the minimum Ct value to first achieve complete inactivation within the full-scale contactor.

Seventeen of the experiments were performed by collecting one sample from each of the five channels of the contactor. For these experiments, complete inactivation usually occurred within the first channel. Sampling from each channel was performed in order to determine if complete inactivation was maintained throughout the contactor without any occurrence of regrowth or short-circuiting. For three experiments, five samples were collected at ten foot intervals from the first channel in order to get a better estimate of a Ct value. Even for these samples, the contact times were too long to prevent an overestimate of the Ct value and the data only provide a conservative estimate of the smallest Ct value required to consistently achieve complete inactivation.

The conservative estimates of the Ct values to achieve complete inactivation of each target microorganism obtained from the first channel are summarized in Table 5-4. The data obtained from the first channel indicate that a total coliform density of ≤2.2 MPN/100 mL was consistently meet at a Ct value of ≤ 46 mg/L•min. This is similar to the Ct value observed from the bench-scale kinetic experiments. Whenever the ≤2.2 MPN/100 mL coliform requirement was meet, the densities of fecal coliform, fecal streptococci, and enterococci were all ≤2.2 organisms/ 100 mL. The heterotrophic plate count, however,

TABLE 5-2

CT VALUES REQUIRED TO INACTIVATE TARGET BACTERIA BELOW DETECTION LIMITS IN BENCH-SCALE SYSTEM

Microorganism	CT Value mg/L.min
Total Coliform	≤ 21
Fecal Coliform	≤ 21
Hetertrophic Place Count	>57 (>150)*

* Based on the 2-hour contact time experiments

TABLE 5-3

CONTACT TIME AND CT VALUE CALCULATION FOR FULL-SCALE SYSTEM

Sampling Location	Sample ID#	Contact Time (V/Q), min.	CT, mg/L•min
Influent	CL-IN	0	0
A	CL-A	$\frac{((116*23/25.75)*543.1}{(Q*10E6/1440))} = T_A$	$C_A * T_A = CT_A$
B	CL-B	$\frac{[(116*2.2/25.75) + (2*116)]*543.1}{(Q*10E6/1440))} = T_B$	$[C_B*(T_B-T_A)]+CT_A = CT_B$
C	CL-C	$\frac{[(116*2.2/25.75) + (3*116)]*543.1}{(Q*10E6/1440))} = T_C$	$[C_C*(T_C-T_B)]+CT_B = CT_C$
D	CL-D	$\frac{[(116*23/25.75) + (3*116)]*543.1}{(Q*10E6/1440))} = T_D$	$[C_D*(T_D-T_C)]+CT_C = CT_D$
E	CL-E	$\frac{(116*5*543.1)}{(Q*10E6/1440))} = T_E$	$[C_E*(T_E-T_D)]+CT_D = CT_E$
A'	CL-A	$10*543.1/(Q*10E6/1440) = T_{A'}$	$C_A * T_A = CT_A$
B'	CL-B	$20*543.1/(Q*10E6/1440) = T_{B'}$	$[C_B*(T_B-T_A)]+CT_A = CT_B$
C'	CL-C	$30*543.1/(Q*10E6/1440) = T_{C'}$	$[C_C*(T_C-T_B)]+CT_B = CT_C$
D'	CL-D	$40*543.1/(Q*10E6/1440) = T_{D'}$	$[C_D*(T_D-T_C)]+CT_C = CT_D$
E'	CL-E	$50*543.1/(Q*10E6/1440) = T_{E'}$	$[C_E*(T_E-T_D)]+CT_D = CT_E$
F	CL-F	$110*543.1/(Q*10E6/1440) = T_F$	$[C_F*(T_F-T_E)]+CT_E = CT_E$

TABLE 5-4

CT VALUES TO INACTIVATE TARGET BACTERIA BELOW DETECTION LIMITS IN FULL-SCALE SYSTEM

Microorganism	Ct Value, mg. min/L
Total Coliform	≤ 43
Fecal Coliform	≤ 30
Fecal Streptococci	<5
Enterococci	<5
Hetertrophic Plate Count	>160

were usually not completely inactivated at this Ct value and as many as 1.8 logs could still be present when all the other organisms were inactivated.

Also of note was the fact that on several occasions, the coliform density increased in the fourth and fifth channel of the contactor even though the coliform had been completely inactivated in the previous channel. The exact cause of this was not investigated. It could have been the result of sampling contamination, analytical error, regrowth, or short-circuiting. Routine coliform monitoring data obtained from the Regional Plant also showed positive coliform densities for the chlorine contactor effluent during the same period the increase in the fourth and fifth channels was observed for the study samples.

Comparison of Bench-Scale and Full-Scale Chlorine Disinfection

The bench-scale kinetic experiments and the full-scale samples collected from the first channel of the chlorine contactor provided similar estimates of the Ct value required to achieve ≤2.2 total coliform/100 mL. A value of ≤21 mg/L•min was obtained at bench-scale and ≤46 mg/L•min was obtained at full-scale. A higher Ct value is probably obtained for the full-scale data because of the larger sources of error associated with the full-scale experiments. At both bench-scale and full-scale, whenever the total coliform were reduced to ≤2.2/100 mL all the other target organisms were completely inactivated with the exception of heterotrophic plate count. As many as 2.9 logs at bench-scale and 1.5 logs at full-scale were still viable when all the other target organisms were inactivated.

UV DISINFECTION RESULTS

Inactivation of bacteria by a disinfectant is classically described by an empirical first order kinetic model commonly referred to as Chick's Law ($\ln N/N_O=-kt$). First order kinetics is also assumed to describe the inactivation of bacteria by UV radiation ($\log N/N_O=-kIt$). UV radiation is a physical rather than chemical form of inactivation and cannot be described in units of aqueous concentration. UV dose is described in terms of the UV intensity (I) multiplied by the exposure time (t). The intensity is the rate at which the energy is being delivered to the liquid. Multiplying this energy delivery rate by the exposure time expresses the quantity of energy delivered to the liquid.

UV inactivation data plotted in accordance with Chick's Law typically exhibit the same tailing effect that is observed for chemical disinfection. This tailing phenomena represents

a decrease in the inactivation rate at higher doses and it is attributed to the occlusion of bacteria within particulate matter which prevents their exposure to the UV light. The accuracy of the estimate of the dose required to affect a 4-log kill for a bacterial indicator organism group is dependent on the region of the inactivation curve were 4-log kill is obtained. If the 4-log kill dose is in the tailing portion of the curve, it is more difficult to accurately estimate the dose. In this circumstance, the Collins-Selleck model can be applied to the data by plotting the log of the UV dose as a function of the log inactivation data.

Calculation of UV Dose

The average UV intensities reported for the bench-scale and full-scale reactors utilized in this study were derived from the single point source summation (SPSS) calculation method developed by Trojan Technologies, Inc. for use with their bench-scale and full-scale equipment. The SPSS is a two dimensional model which assumes that the UV intensity at any point in the system originates from a single point source and the light from this point source is spread over the circumference of a disc that intersects the point of interest. The point source summation (PSS) calculation method specified in the California Department of Health Services (DHS) UV Disinfection Guidelines for Wastewater Reclamation in California and described in detail in the U.S. EPA Design Manual for Disinfection of Municipal Wastewater (1986) is a three dimensional model where the UV intensity at a single point in the system is calculated by summing the intensities received at that point from all point sources in the system which are assumed to radiate light spread over spheres.

Parameters that are considered in both the SPSS and PSS methods are the lamp and reactor geometry, transmittance of the quartz sleeves, and transmittance of the wastewater flowing through the UV system. The average UV intensity calculated by these methods corresponds to 100% UV lamp output which occurs after the first 100 hours of lamp operation. The UV intensity calculated from the SPSS or PSS methods is then corrected for lamp age before arriving at the average UV reactor intensity. The decline in percentage lamp output as a function of lamp age in hours is provided by the manufacturer. Seventy percent output is considered to be the end of usable lamp life. The average UV reactor intensity corrected for lamp age is then multiplied by the exposure time to obtain the average reactor UV dose. The bench-scale UV reactor behaves hydraulically as a plugflow reactor due to the high aspect ratio of the reactor geometry. The exposure times for the bench-scale unit can then be determined by dividing the net reactor volume by the flow rate

through the system. The net reactor volume was obtained from the total reactor volume minus any reactor volume extending beyond the length of the UV lamp minus the volume occupied by the UV lamps. The full-scale reactor was also shown to obey plugflow hydraulics at 86% of peak flow. Details of the tracer test are presented in Section 8.

The difference between SPSS and PSS calculated UV doses have been reported for UV pilot units by Darby (1993) and others (Ca DHS UV Disinfection Guidelines, 1993). The SPSS is a more conservative estimate of dose and in these direct comparisons, the SPSS dose underestimated the PSS dose by approximately 12 percent. The Ca. DHS UV disinfection guidelines for UV dose calculations call for estimations to be based on restrictive worst-case conditons. A direct comparison of the SPSS and PSS calculated UV intensities for the full-scale UV reactor geometry employed in this study was made under worst-case conditions of minimum observed fluid transmittance, maxium lamp fouling, and maximum lamp age. The values used for these worst case conditions were:

UV Transmittance	71.6%
Transparency Reduction Factor	0.70 (due to sleeve fouling)
Lamp Output Reduction Factor	0.70 (due to lamp age)

The equation relating the SPSS UV intensity to the PSS UV intensity:

$$\text{SPSS UV Intensity} = 0.80 * \text{PSS UV Intensity}$$

indicates that the SPSS calculation method will underestimate the PSS calculatied UV dose by 20 percent. Therefore, the SPSS calculated UV doses reported in this study can be converted to equivalent PSS calculated UV doses by multiplying the SPSS doses by a factor of 1.25.

The PSS method has been specified in the California DHS UV Disinfection Guidelines for Wastewater Reclamation in California as the standard method for computation of the average UV radiation intensity within the UV reactor. The shortcoming of both the PSS and SPSS computational approaches is that they do not account for lamp fouling. These methods will therefore overestimate the true UV intensity unless the lamps have just been cleaned. This is an important concern for full-scale systems that will not clean lamps on a daily basis, but must demonstrate continuous maintenance of a minimum UV intensity. Alternative methods for calculating UV reactor intensity which should account for lamp

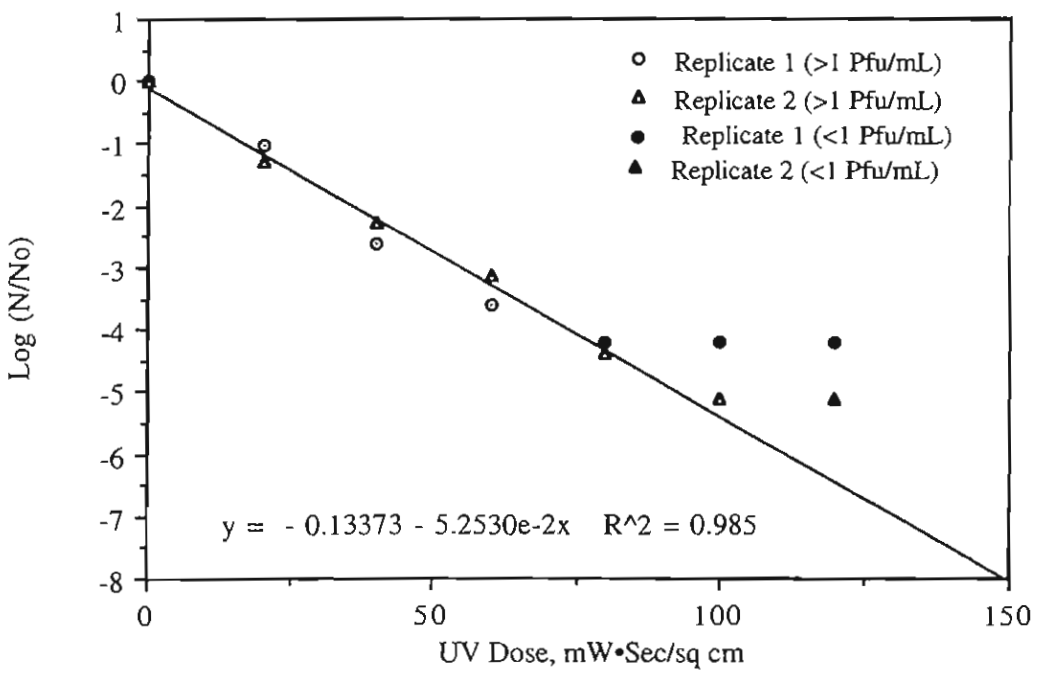
fouling (loss of transmittance through the quartz sleeves) are chemical actinometry and biological assays.

Calibration of the UV Dose by a Bioassay Procedure

An MS2 bacteriophage biological assay was performed in duplicate utilizing a collimated beam apparatus in order to obtain a UV dose-response curve to use for calibrating the bench-scale and full-scale UV reactor doses derived from the SPSS method. Seeded MS2 bacteriophage was included with each bench-scale inactivation experiment and each clean lamp full-scale inactivation experiment. This allowed the average UV intensities calculated at bench-scale and full-scale by the SPSS method to be normalized against the bioassay calibration method. The MS2 bacteriophage calibration curve obtained using the collimated beam apparatus is presented in Figure 5-3.

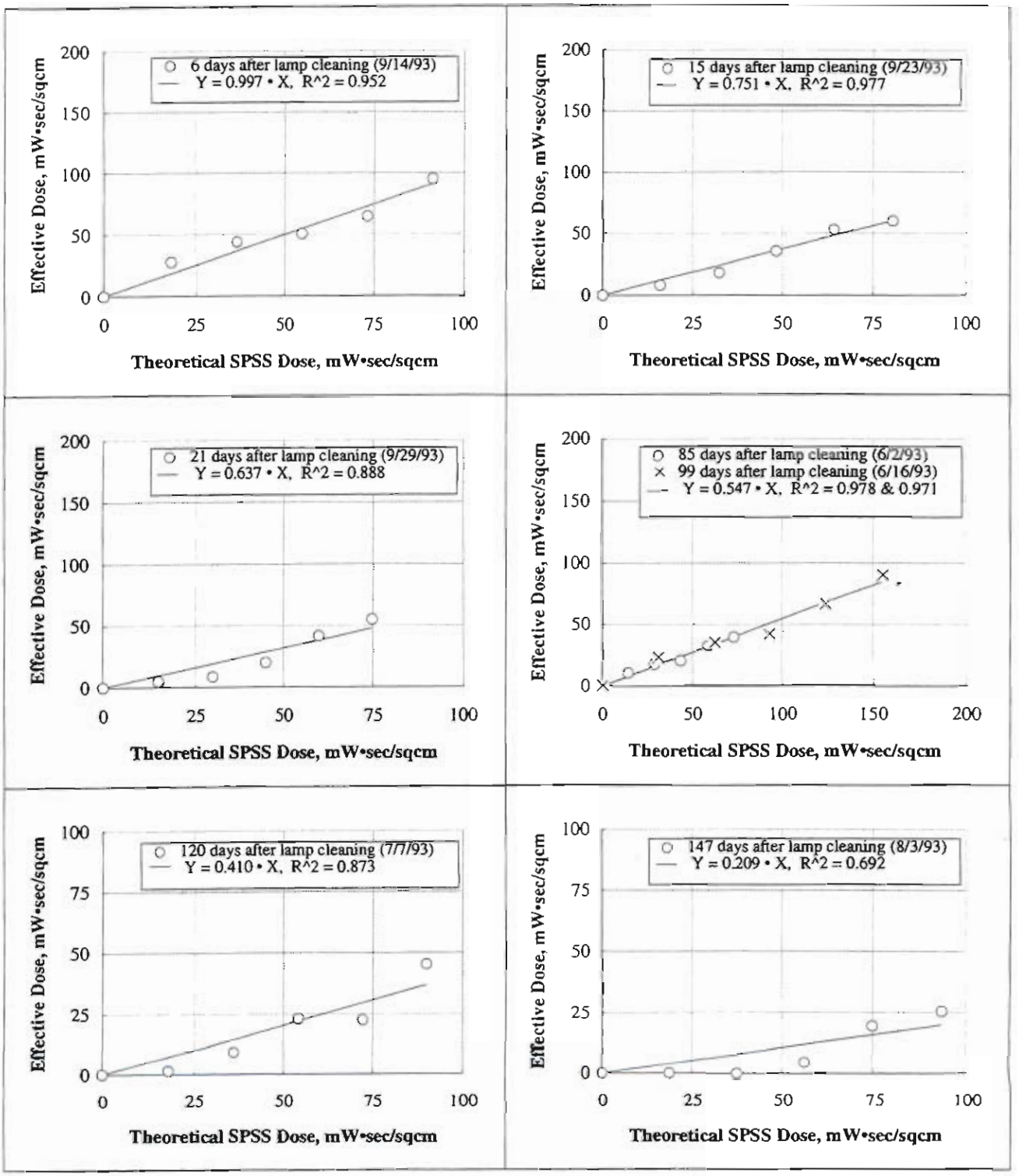
Seeded MS2 bacteriophage was included with seven full-scale inactivation experiments performed at various stages of lamp fouling. The MS2 calculated effective UV doses were plotted in Figure 5-4a as a function of the SPSS calculated theoretical UV doses for the seven different elapsed times after lamp cleaning. If the two methods of estimating UV intensity are equivalent in the absence of lamp fouling, then the data obtained 6 days after lamp cleaning (essentially no fouling) should fit a linear regression with a slope of 1.0. The data obtained from the Trojan 3000 system installed at the EVMWD Regional Plant do show a high degree of correlation between the two UV dose estimation methods (correlation coefficient = 0.952 and a slope of 0.997) in the absence of lamp fouling. Based on this experimentally established correlation in the absence of lamp fouling, correlation of these two methods during various stages of lamp fouling should also fit a linear regression with the percentage lamp fouling equivalent to (1 - slope) x 100. A single summary plot of all the data is presented in Figure 5-4b to demonstrate the decrease in slope with elapsed time after lamp cleaning. All data points in Figure 5-4a were empirically determined with the exception of the origin. This data point is theoretically based on the fact that no MS2 inactivation should occur when the lamps are turned off. The data from five MS2 control runs, presented in Figure 5-5, demonstrates no appreciable loss of the MS2 during passage through the UV reactor when the lamps are turned off.

A plot of the percentage lamp fouling as a function of the number of days since lamp cleaning was then plotted as shown in Figure 5-6 to determine whether the lamp fouling rate appears to be linear with time. The 0.809 correlation coefficient for the linear



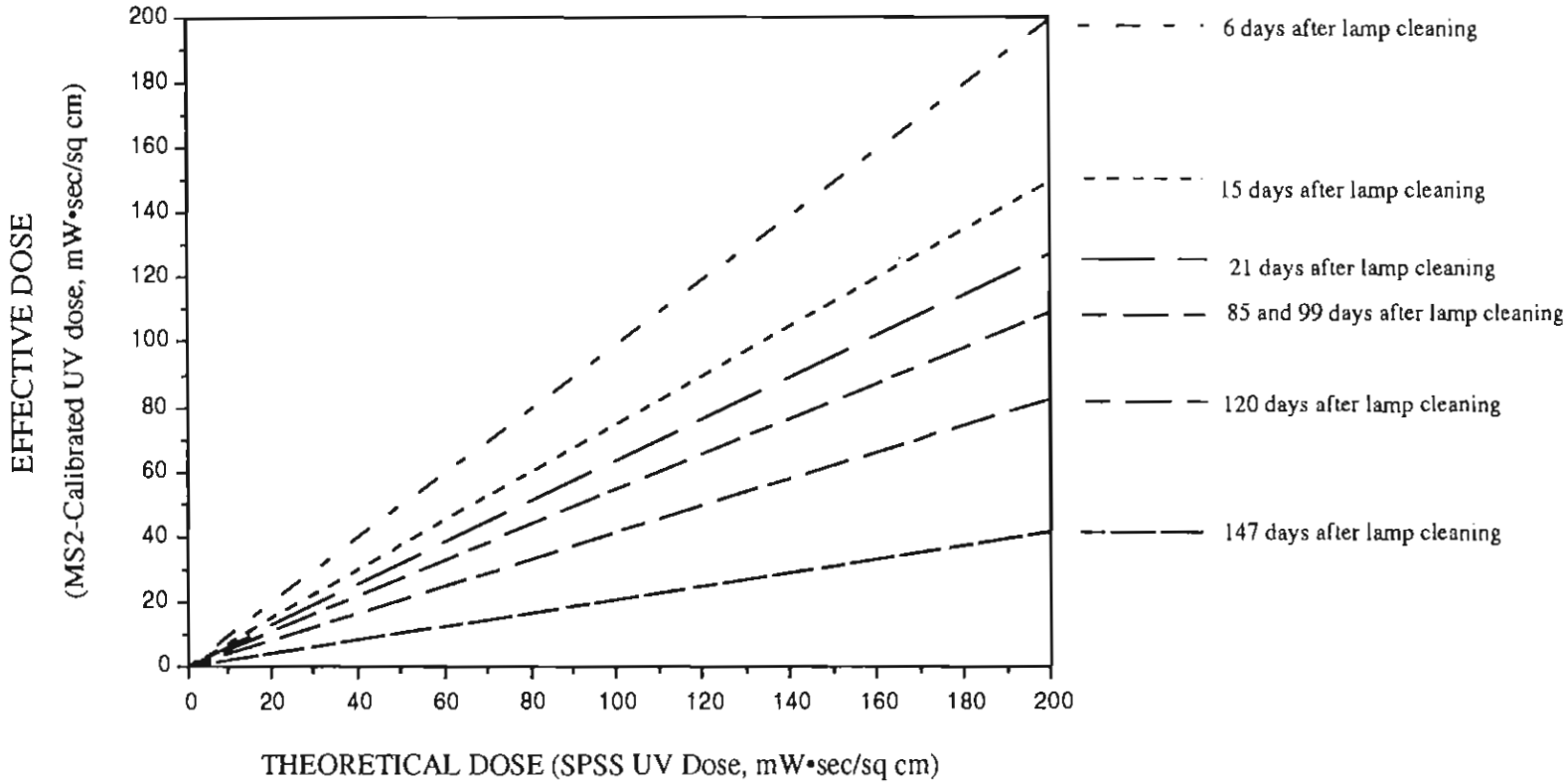
MS2 BACTERIOPHAGE INACTIVATION AS A FUNCTION OF UV DOSE FOR A COLLIMATED BEAM APPARATUS

FIGURE 5-3



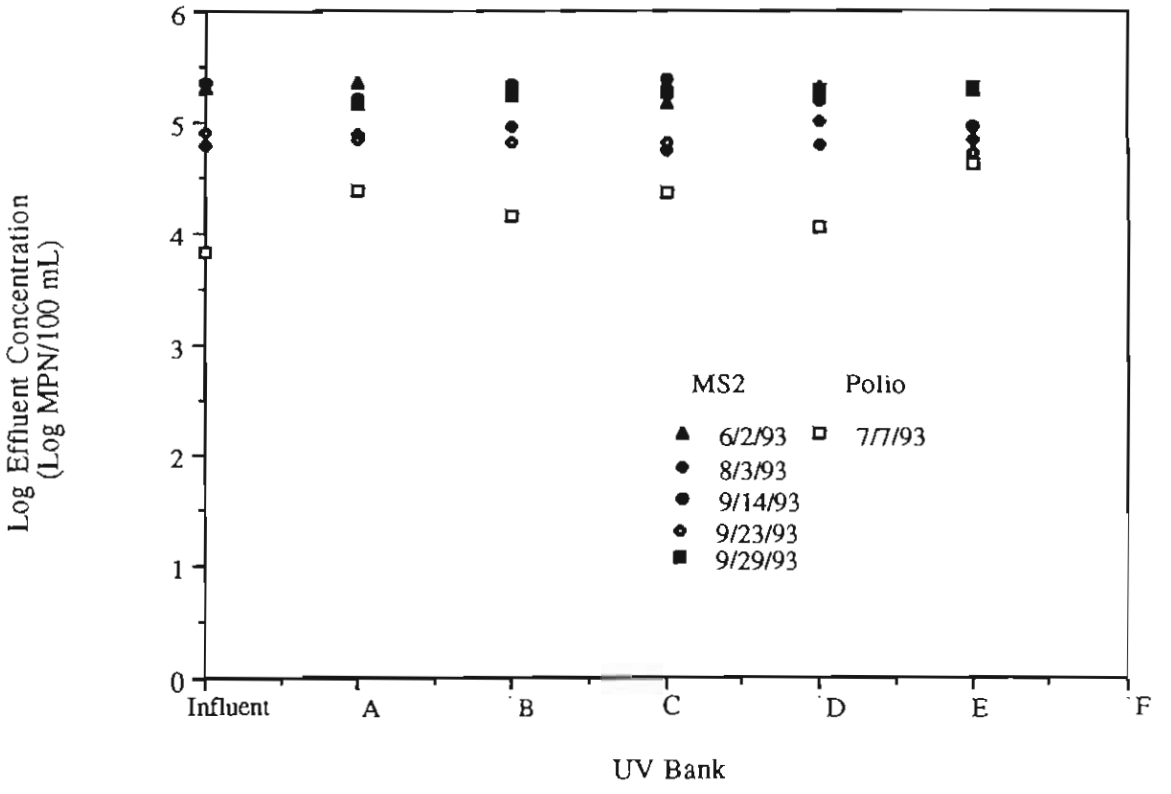
CORRELATION OF MS2-CALIBRATED UV DOSE (EFFECTIVE DOSE) AND SPSS MODEL CALCULATED DOSE AS A FUNCTION OF ELAPSED TIME AFTER LAMP CLEANING

FIGURE 5-4a



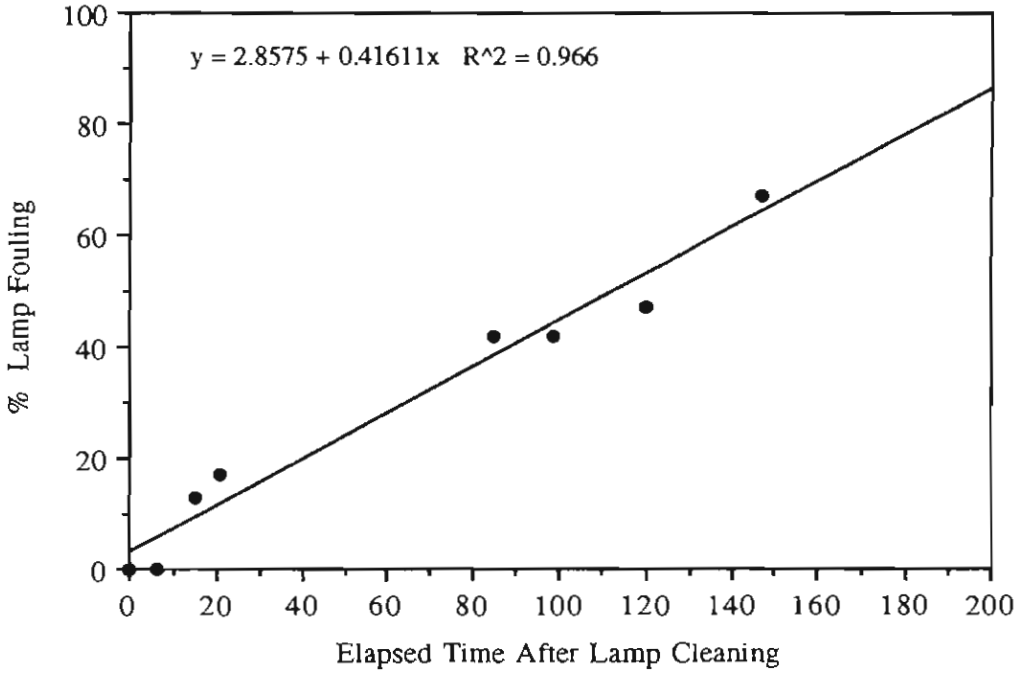
CORRELATION OF MS2 CALIBRATED UV DOSE AND SPSS MODEL CALCULATED DOSE AS A FUNCTION OF ELAPSED TIME AFTER LAMP CLEANING

FIGURE 5-4b



MS2 BACTERIOPHAGE AND POLIO SEED CONTROL DATA FOR THE FULL-SCALE UV REACTOR

FIGURE 5-5



PERCENTAGE LAMP FOULING AS A FUNCTION OF ELAPSED TIME AFTER LAMP CLEANING (FOULING CURVE)

FIGURE 5-6

regression through the data points appears to support a linear fouling rate. Making use of this linear fouling rate provides a way to correct SPSS calculated full-scale UV intensities for the decrease in UV intensity due to lamp fouling even if MS2 bacteriophage seedings were not performed for an experiment . This type of curve should also provide the treatment plant with an operational tool for estimating the true average UV reactor intensity at any time after lamp cleaning. This is of tremendous practical importance, because the technology is not currently available for a plant to accurately monitor the average UV intensity within a full-scale reactor by means of an in-line probe.

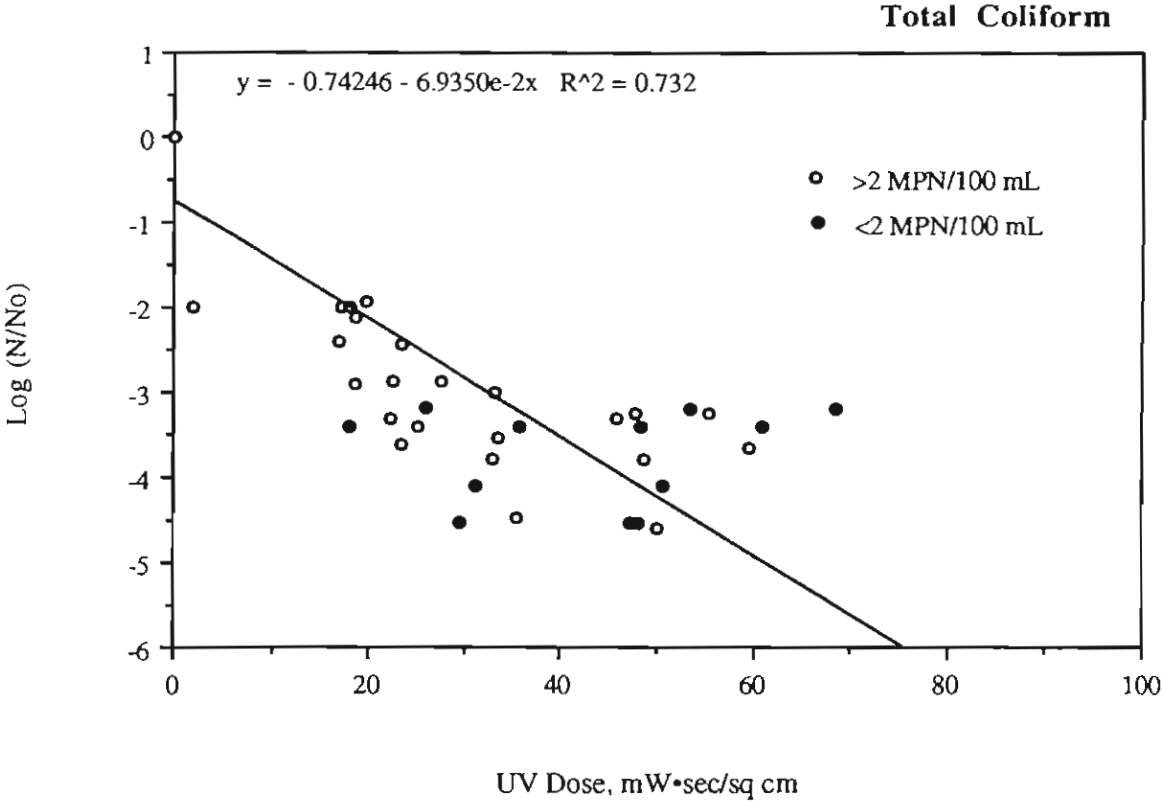
UV Disinfection Results Obtained from Bench-Scale Experiments

Seven sets of bench-scale UV inactivation experiments were performed to determine the minimum UV dose required to achieve total coliform ≤2.2 MPN/100 mL and inactivation below detection limits for the other target organisms. This data are presented in Figures 5-7 through Figure 5-11 for each of the target organisms. The doses required to achieve the requisite level of inactivation were 53 mW•sec/sq cm for total coliform, 35 mW•sec/sq cm for fecal coliform, 34 mW•sec/sq cm for fecal streptococci, 38 mW•sec/sq cm for enterococci, and 77 mW•sec/sq cm for heterotrophic plate count.

UV Disinfection Results Obtained from Full-Scale Experiments

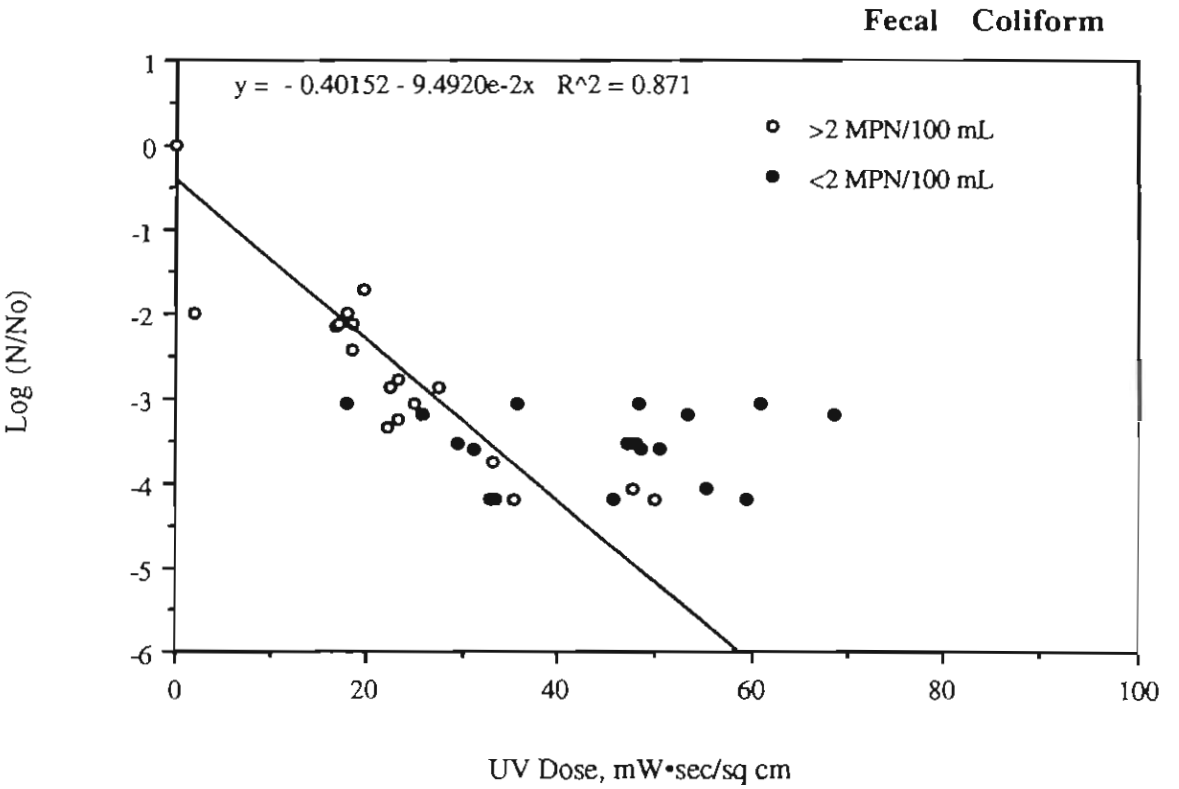
Twenty-one sets of full-scale UV inactivation experiments were performed to determine the minimum UV dose required to achieve total coliform ≤2.2 MPN/100 mL and complete inactivation of the other target organisms. Experiments Number 1 through Number 4 were performed using uncovered lamps. Experiments Number 5 through Number 21 were performed with 60 percent of each UV lamp covered with an aluminum sleeve in order to obtain lower UV doses and the upper portion of the inactivation curves. Data from experiments Number 1 and Number 11 were anomalous and were not included in determination of the UV inactivation doses.

During 6 of the 21 experiments, "control" samples were collected immediately after each UV bank when the UV lamps were turned off. These samples were analyzed for total coliform, fecal coliform, fecal streptococci, and enterococci and compared with the concentrations measured in the influent to the UV system. This control data, summarized in Figures 5-12 and 5-13 demonstrate that no appreciable loss of bacteria was occurring during passage through the UV reactor.



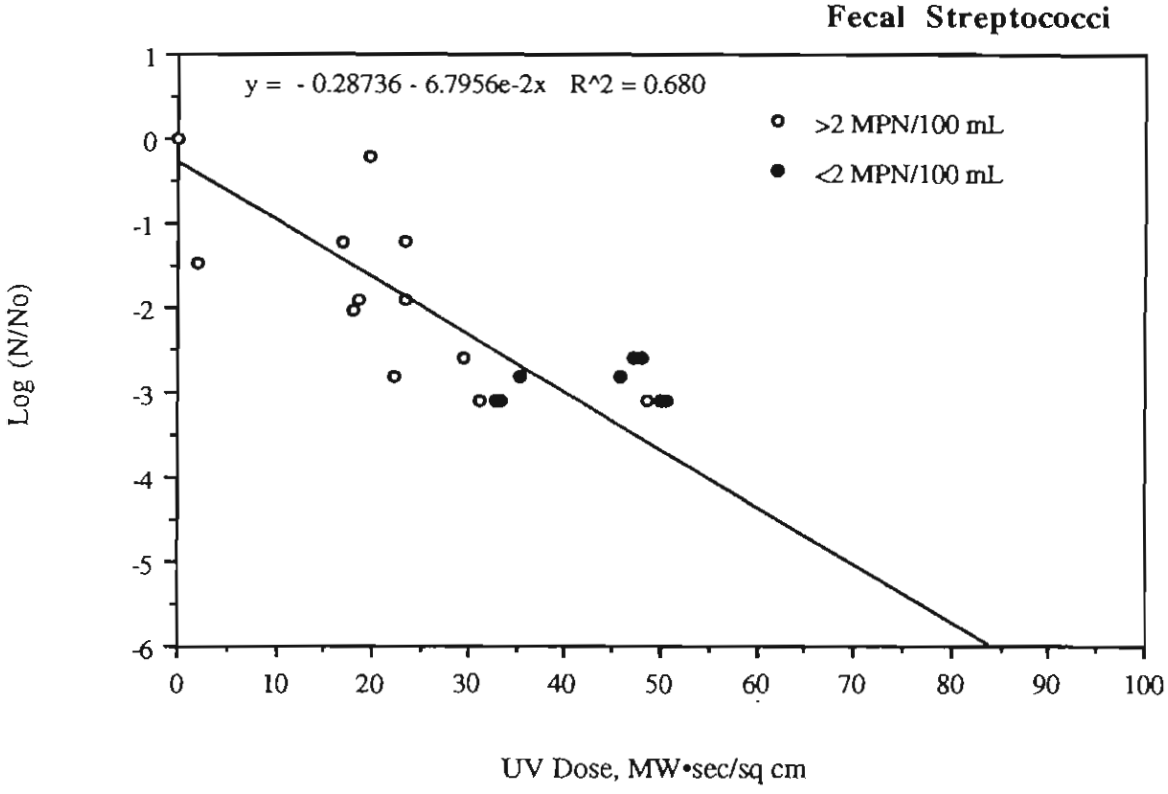
BENCH-SCALE UV INACTIVATION OF TOTAL COLIFORM

FIGURE 5-7



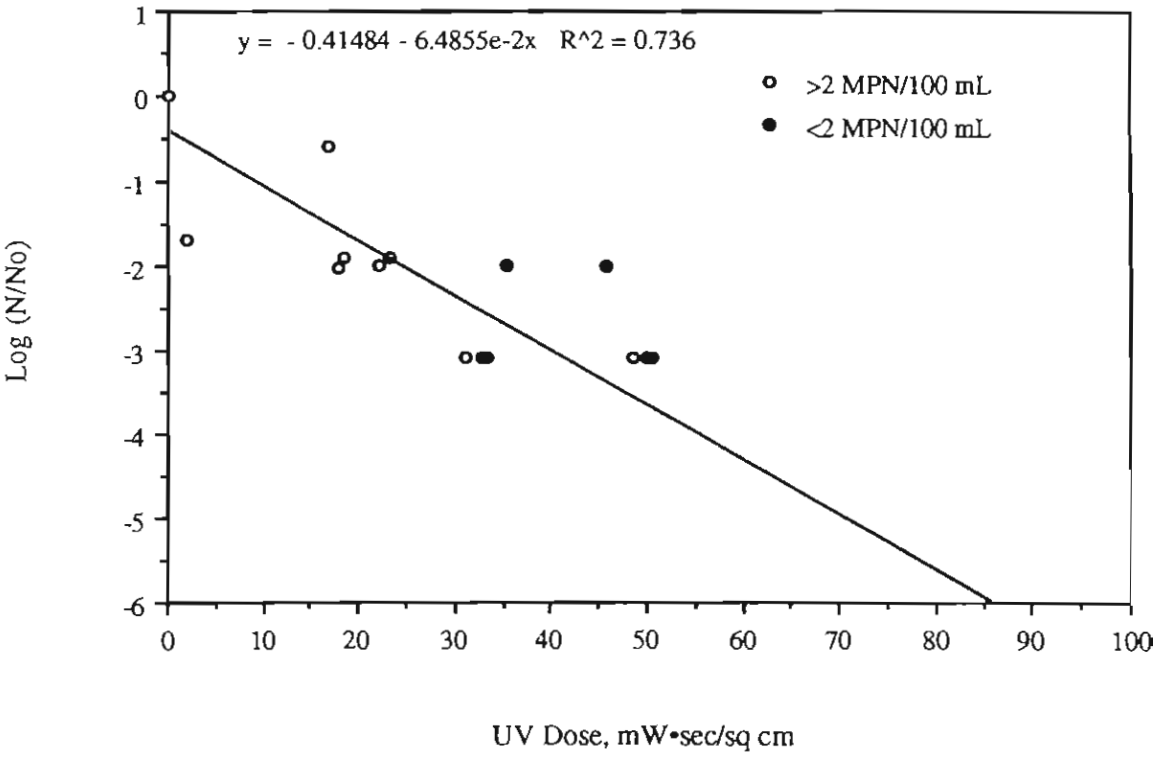
BENCH-SCALE UV INACTIVATION OF FECAL COLIFORM

FIGURE 5-8



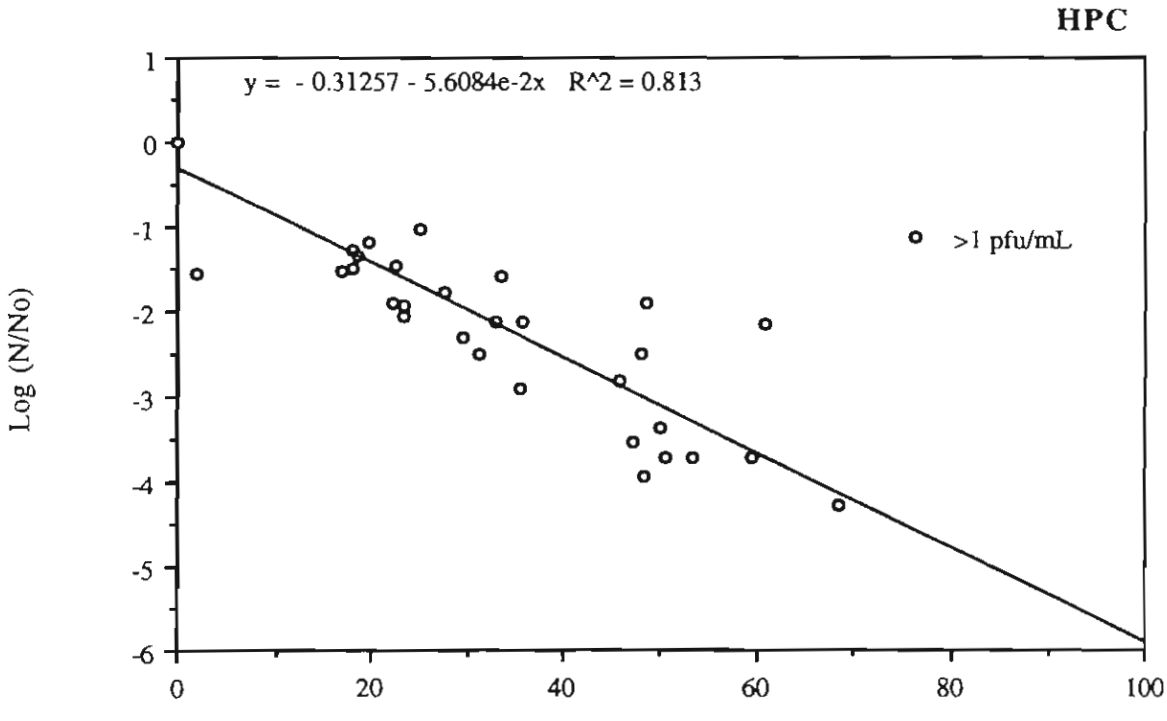
BENCH-SCALE UV INACTIVATION OF FECAL STREPTOCOCCI

FIGURE 5-9



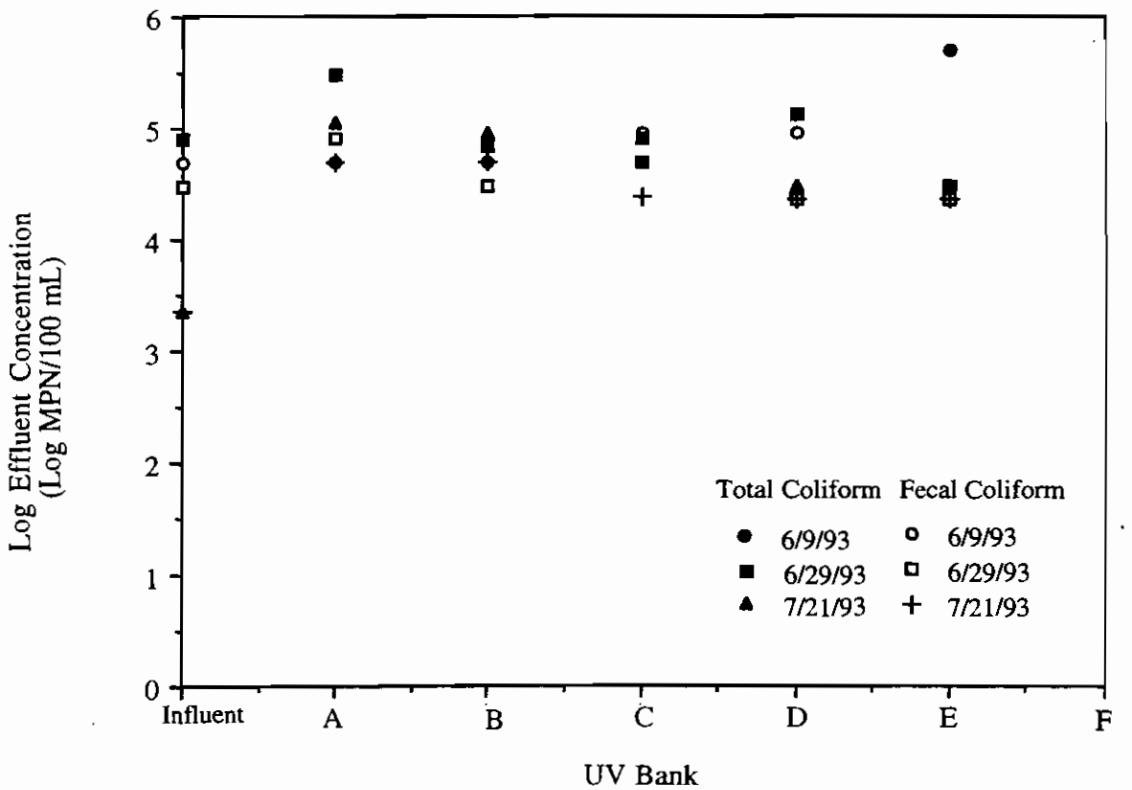
BENCH-SCALE UV INACTIVATION OF ENTEROCOCCI

FIGURE 5-10



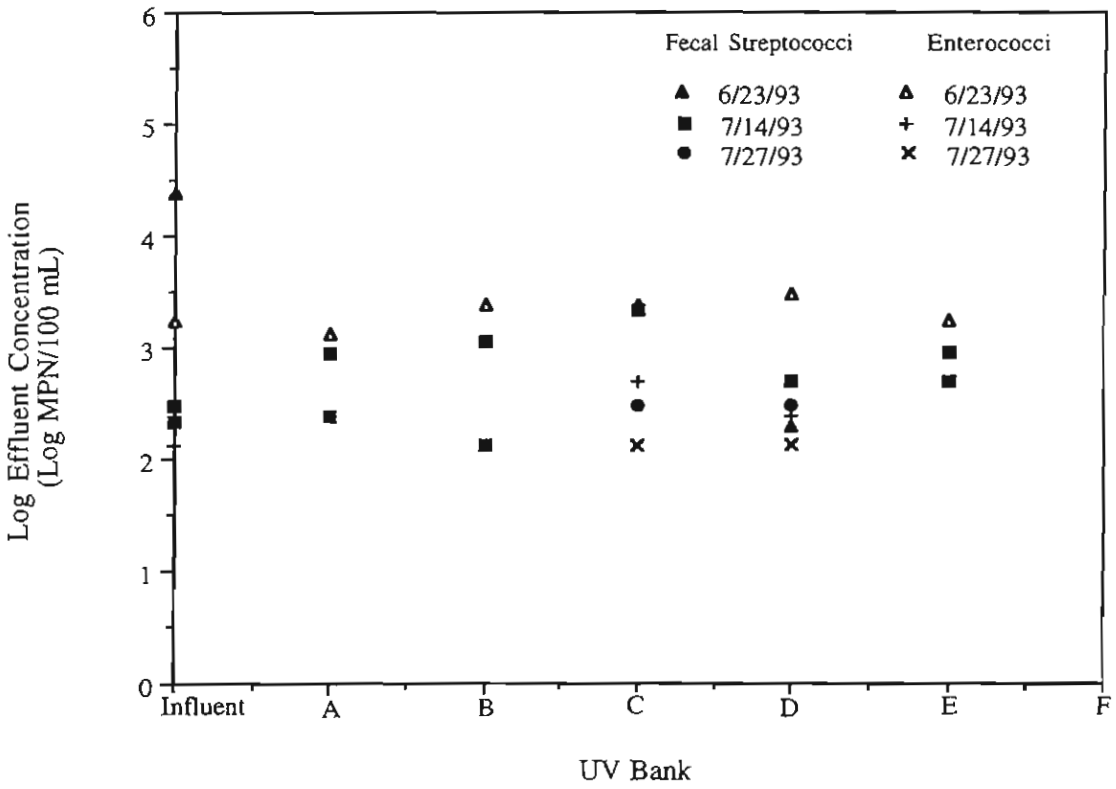
BENCH-SCALE UV INACTIVATION OF HPC

FIGURE 5-11



INDIGENOUS TOTAL AND FECAL COLIFORM CONTROL DATA FOR THE FULL-SCALE UV REACTOR

FIGURE 5-12



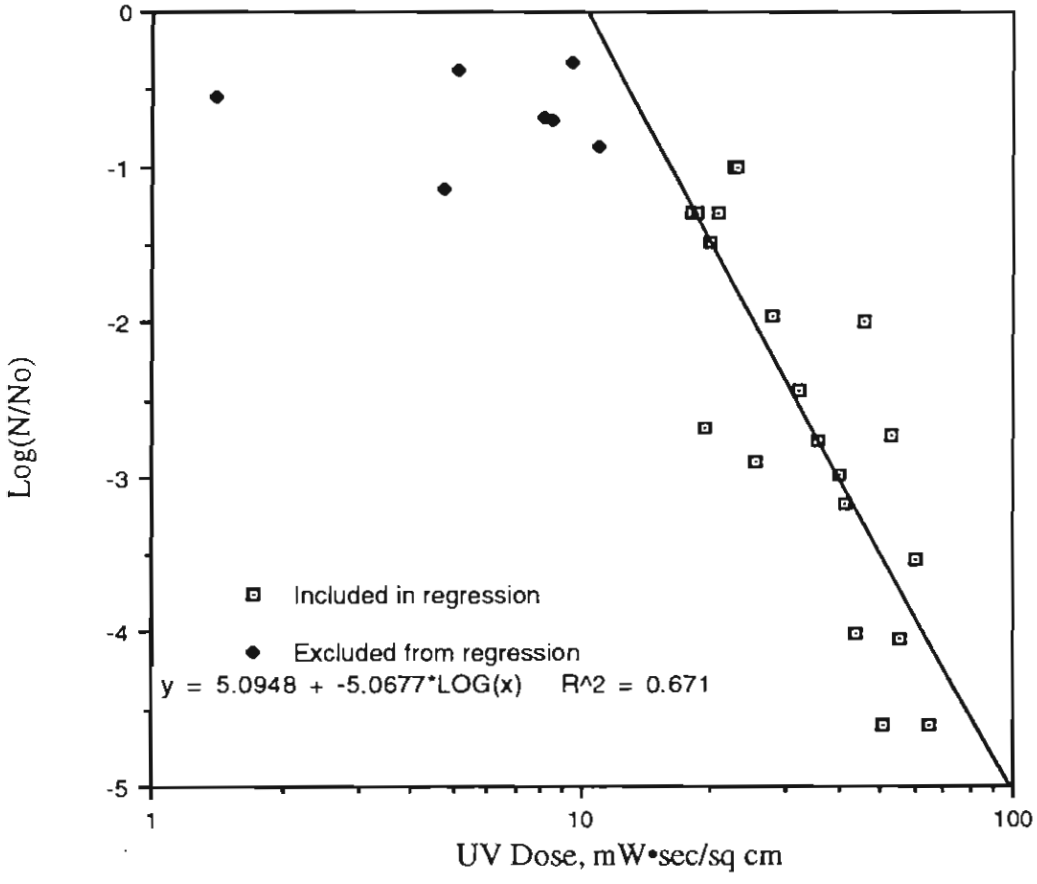
INDIGENOUS FECAL STREPTOCOCCI AND ENTEROCOCCI CONTROL DATA FOR THE FULL-SCALE UV REACTOR

FIGURE 5-13

The UV lamps were in various stages of fouling during the 19 experimental runs. For 6 of the experimental runs, MS2 seeding experiments were performed and provided a direct way to correct the SPSS calculated UV dose for the impact of fouling. The inactivation data for these 6 experimental runs are presented in Figure 5-14 through Figure 5-18. An obvious lag is exhibited at the lower UV doses and data points corresponding to UV doses less than 10 mW•sec/sq cm were not included in the linear regression. For the remaining 13 experimental runs, the SPSS dose was corrected for fouling through use of the fouling curve. The inactivation data for these 13 experimental runs are presented in Figure 5-19 through 5-23. The lag is less obvious in these plots because of the wider x-axis scale, but it is still present and data points corresponding to UV doses less than 10 mW•sec/sq cm were not included in the linear regression. A comparison of the inactivation doses obtained for the six experimental runs corrected based on the MS2 bacteriophage bioassay results and the 13 experimental runs corrected based on the fouling curve are presented in Table 5-5. The relative difference in the doses obtained by the two methods falls within 25 percent for all of the organisms with the exception of HPC. The large difference in doses obtained for HPC can be attributed to the larger amount of scatter in the data. Also presented in Table 5-5 is a comparison of the inactivation doses obtained from the full-scale plant with and without correcting for lamp fouling. These 19 experiments represent a range of 6 to 147 days of elapsed time after lamp cleaning and demonstrate a large overestimation of the inactivation dose when the SPSS model is not corrected for fouling. The 95% confidence interval for each 4-log inactivation dose is also presented in Table 5-5 in parentheses next to each reported dose. The confidence interval was obtained by plotting the 95% confidence bands for the true mean of the Y variable (log N/No) and using the linear regression to calculate the UV dose interval corresponding to this inactivation interval. Comparison of the UV dose confidence intervals indicates no significant difference in the 4-log inactivation doses obtained based on the MS2 bacteriophage bioassay results and those obtained based on the fouling curve and a significant difference between SPSS doses obtained with and without .correction for lamp fouling.

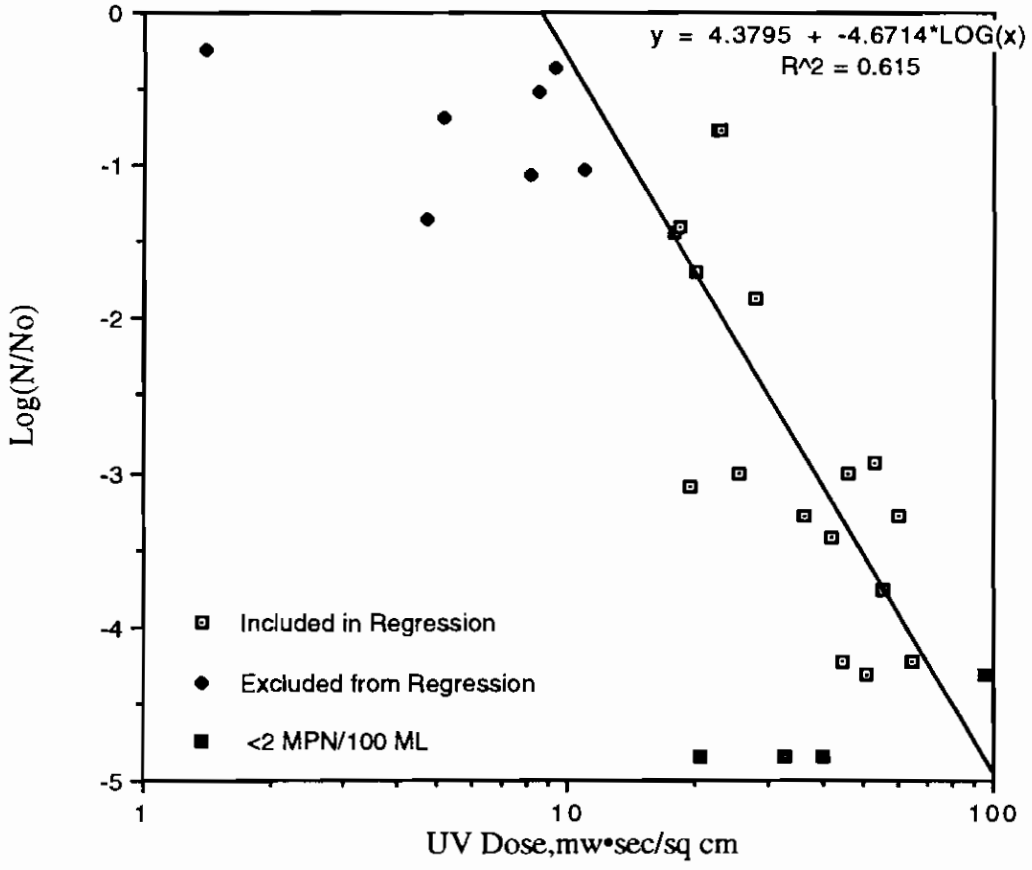
Comparison of Bench-Scale and Full-Scale UV Disinfection

Comparison of the bench-scale inactivation doses with the full-scale inactivation doses is also presented in Table 5-5. No significant difference between the bench-scale and full-scale doses are apparent for any of the target organisms with the exception of fecal coliform, where the bench-scale dose appears to under predict the full-scale dose. There is



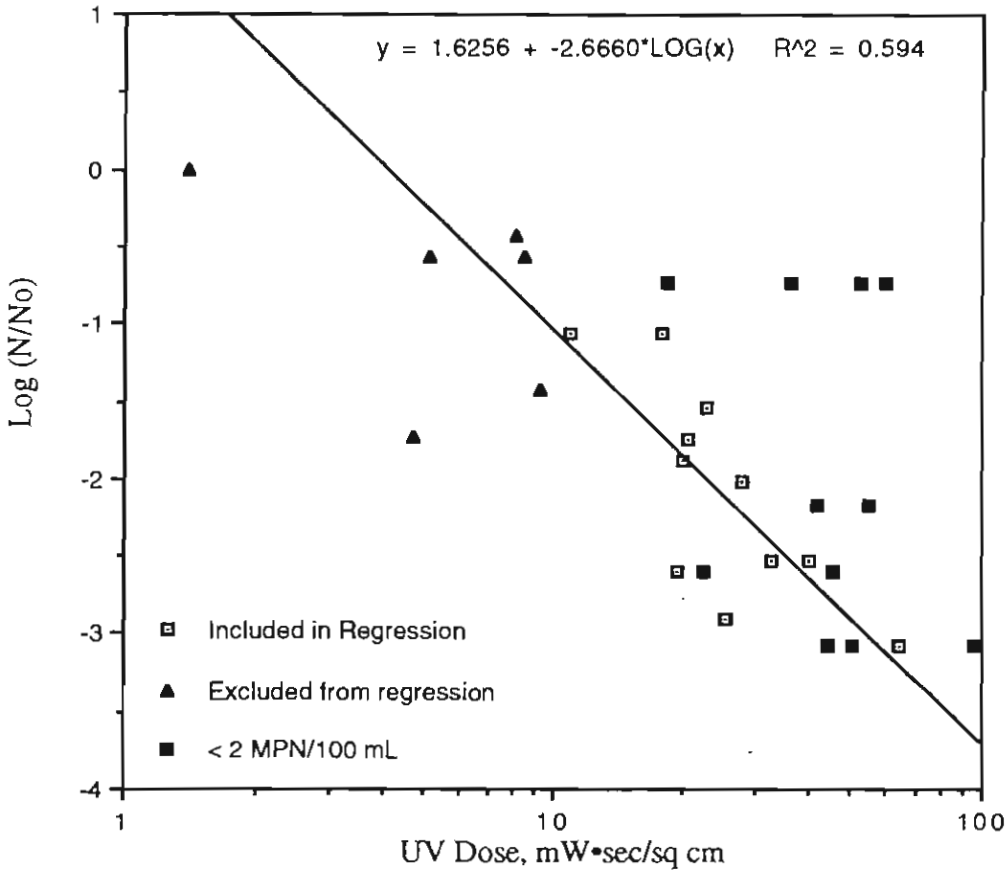
FULL-SCALE UV INACTIVATION OF TOTAL COLIFORM [DOSE ADJUSTED BY MS2 CALIBRATION]

FIGURE 5-14



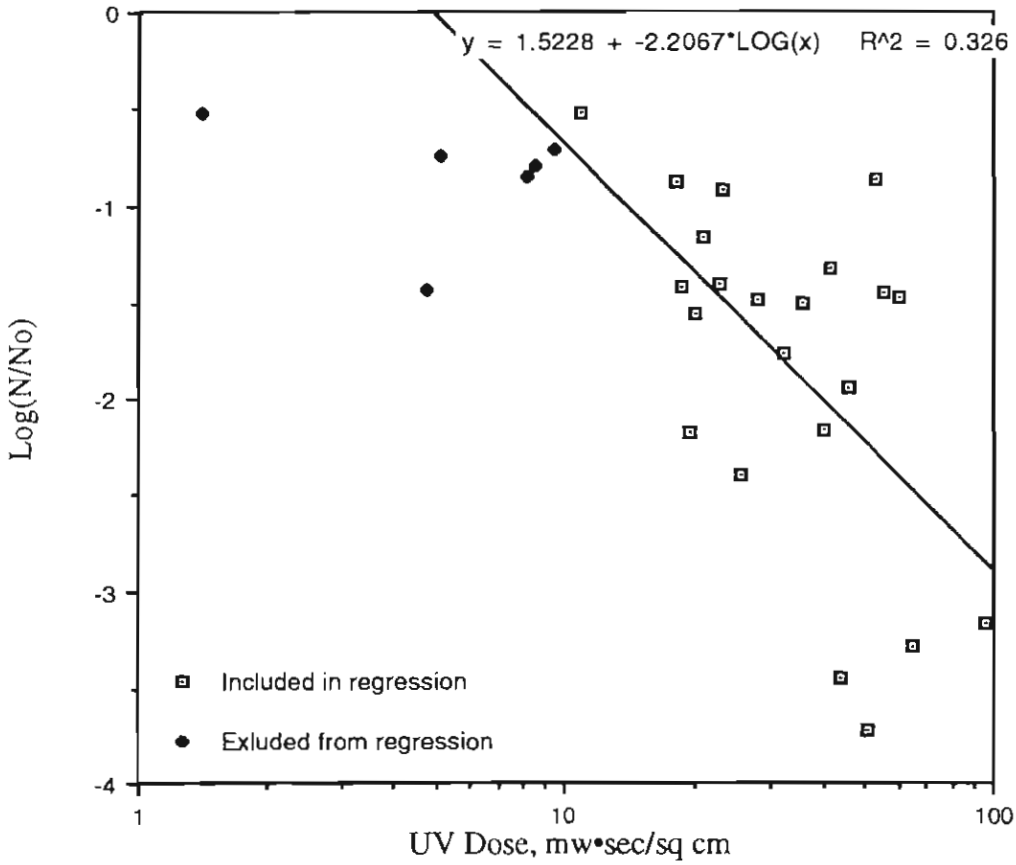
FULL-SCALE UV INACTIVATION OF FECAL COLIFORM [DOSE ADJUSTED BY MS2 CALIBRATION]

FIGURE 5-15



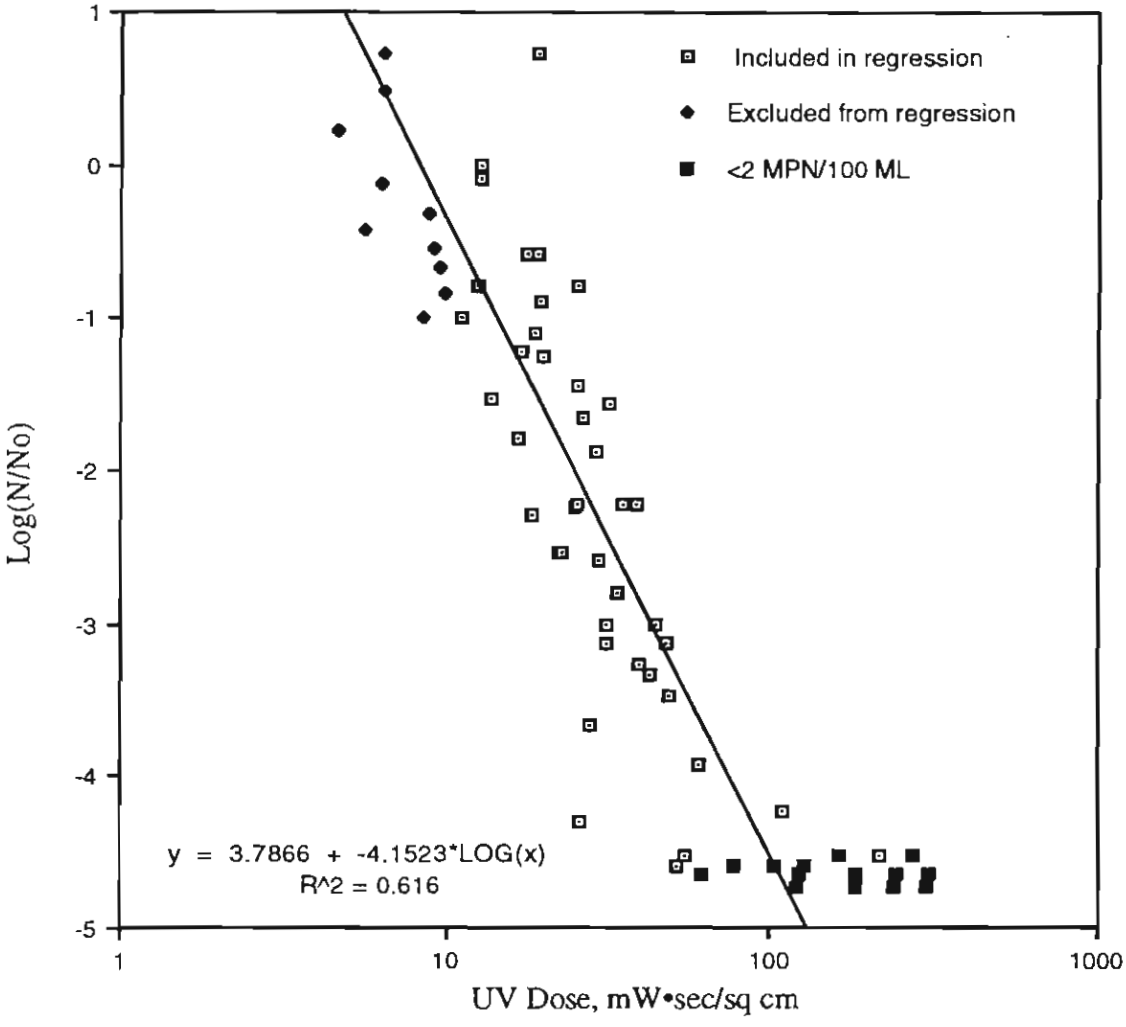
FULL-SCALE UV INACTIVATION OF FECAL STREPTOCOCCI [DOSE ADJUSTED BY MS2 CALIBRATION]

FIGURE 5-16



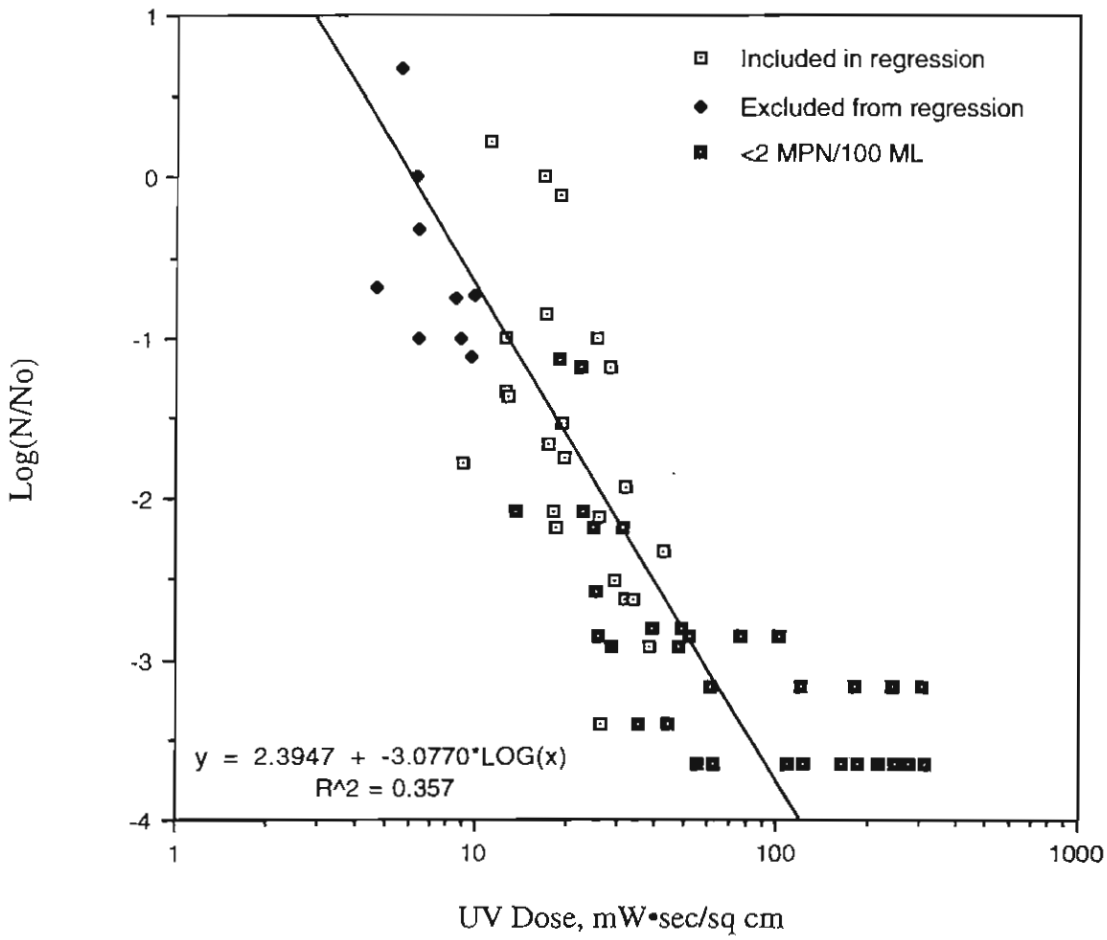
FULL-SCALE UV INACTIVATION OF HPC [DOSE ADJUSTED BY MS2 CALIBRATION]

FIGURE 5-18



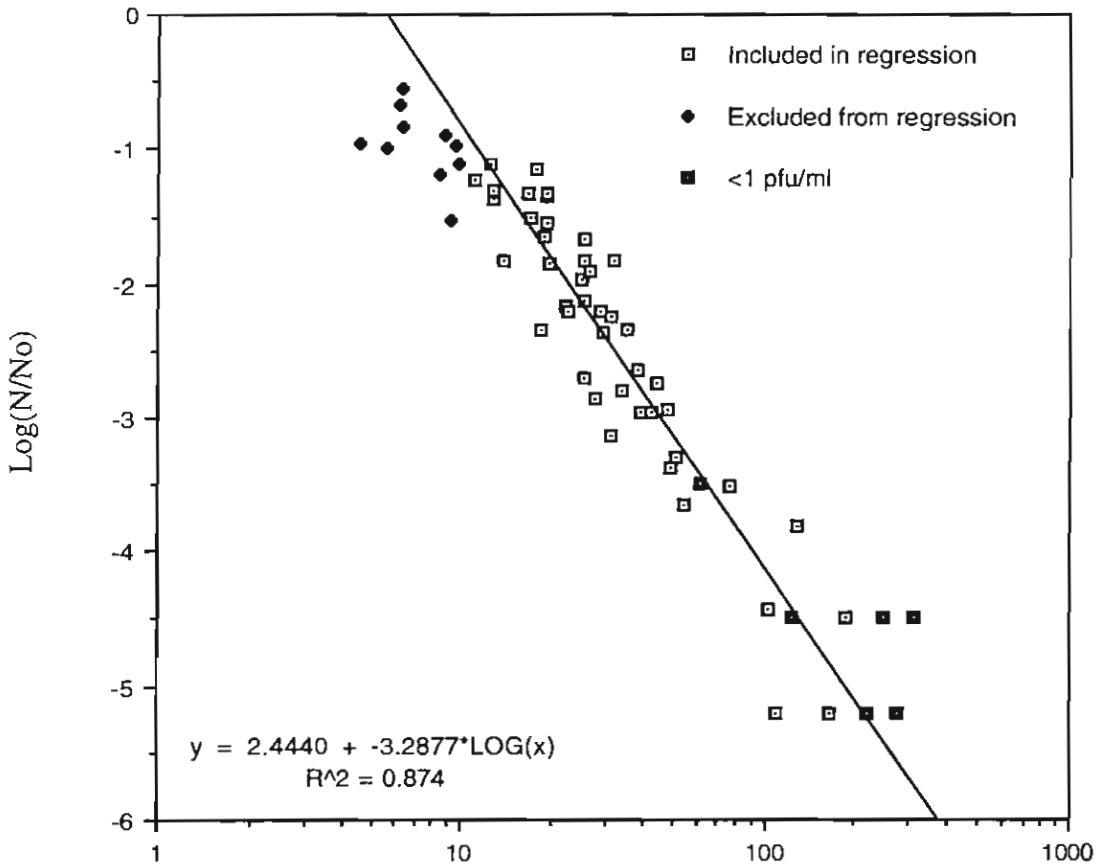
FULL-SCALE UV INACTIVATION OF TOTAL COLIFORM [DOSE ADJUSTED BY FOULING CURVE]

FIGURE 5-19



FULL-SCALE UV INACTIVATION OF FECAL STREPTOCOCCI [DOSE ADJUSTED BY FOULING CURVE]

FIGURE 5-21



FULL-SCALE UV INACTIVATION OF HPC [DOSE ADJUSTED BY FOULING CURVE]

FIGURE 5-23

also significantly more scatter in the HPC data obtained at full-scale when the MS2 seedings were performed.

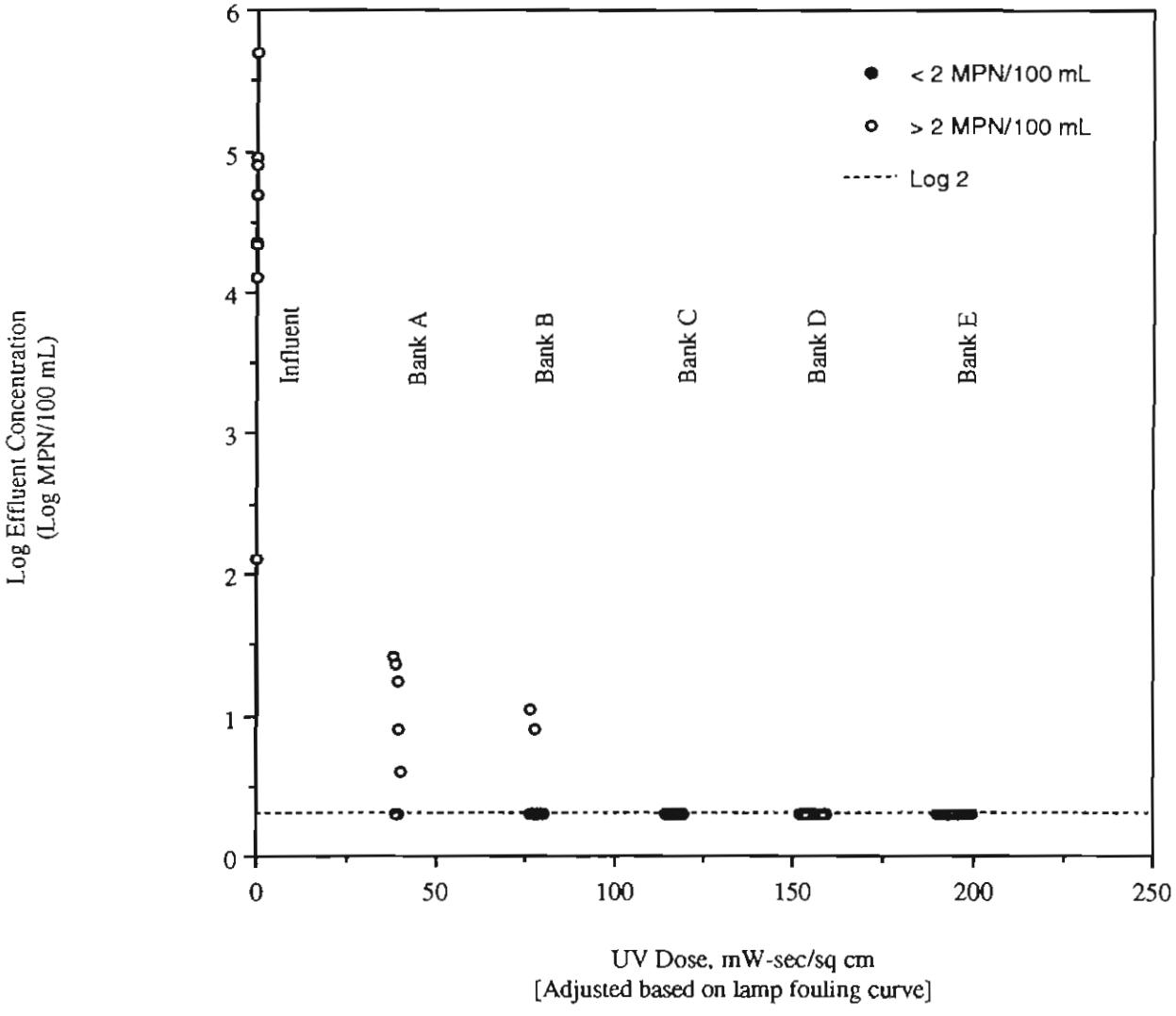
UV Disinfection Results Obtained for Compliance with the California Title 22 Total Coliform Requirement

The aluminum sleeves were removed from the Trojan 3000 System to obtain the higher doses needed to demonstrate compliance with the most restrictive California Wastewater Reclamation Criteria (Title 22, Division 4, Chapter 3 of the California Code of Regulations) that the median number of coliform organisms does not exceed 2.2 per 100 mL and the number of coliform organisms does not exceed 23 per 100 mL in more than one sample within any 30-day period. The median value is determined from the bacteriological results of the last 7 days for which analyses have been completed. Although 4-log inactivation of total coliform was demonstrated at a dose of 75 mW•sec/sq cm from data obtained at full-scale, a higher dose between 80 and 120 mW•sec/sq cm was needed to consistently achieve total coliform ≤2.2/ 100 mL. Samples of the influent and effluent from each of the five banks were sampled each morning for ten consecutive days in November of 1993.

The data obtained from the Trojan 3000 system without any lamp coverage are summarized in Figure 5-24. Inactivation of total coliform to ≤2.2 per 100 mL is consistently achieved for Banks C, D, and E. The range of doses calculated for Bank C from the SPSS method corrected for lamp fouling by the fouling curve was approximately 114 to 120 mW•sec/sq cm during the ten day period. This range in dose is principally due to the difference in flow rates during the ten days. These samples were collected within 21 days of lamp cleaning so lamp fouling did not have a major impact on the calculated dose. This experiment was performed at 70% of nominal lamp life.

Photoreactivation

Some organisms inactivated by UV light are repaired and able to replicate upon exposure to visible light at wavelengths between 310 and 490 nm in a process known as photoreactivation. Photoreactivation has commonly been observed in UV disinfected effluents exposed to visible light under laboratory conditions (U.S. EPA, 1986). Not all organisms appear to be able to photoreactivate and the phenomena has mainly been observed for total and fecal coliform.



COMPLIANCE WITH MOST RESTRICTIVE CALIFORNIA TITLE 22 WASTEWATER RECLAMATION REQUIREMENT (≤2.2 MPN/100 mL)

FIGURE 5-24

The effects of photoreactivation of total and fecal coliform bacteria were evaluated as part of the full-scale UV study by collecting samples of the UV system influent, effluent from Bank A, effluent from Bank C, and effluent from Bank E in accordance with the sampling protocols detailed in Section 3. For these experiments, the UV lamps were not covered with aluminum sleeves. The samples were collected in amber polyethylene bottles and immediately transported to the laboratory for the photoreactivation experiment. Duplicate aliquots were removed from each sample bottle, transferred to Pyrex casserole dishes, and exposed to light in the visible spectrum for one hour. The volume remaining in each amber sample bottle was stored in the dark for the one hour period to be analyzed as "dark reactivation" controls.

Results. The data obtained for total and fecal coliform reactivation are presented in Table 5-6. Unfortunately, no surviving total and fecal coliform were present in any of the UV irradiated samples despite having influent concentrations of 4.3 logs of total coliform and fecal coliform. Because complete inactivation was achieved at each UV bank, no photoreactivation effects were observed as a function of UV dose. The data do indicate, however, that photoreactivation might not be a concern at the EVMWD Regional Plant provided a sufficient UV dose is applied to completely inactivate the total and fecal coliform. Based on the flow rate, lamp age, UV transmittance, and days since lamp cleaning, the UV dose at each bank for this experiment was estimated to be 30 mW•sec/sq cm utilizing the SPSS model and the lamp fouling curve.

TABLE 5-6

PHOTOREACTIVATION EXPERIMENT RESULTS

UV Bank	Dose	Microorganism *			
		Dark Control		Photoreactivated	
		Total Coliform	Fecal Coliform	Total Coliform	Fecal Coliform
	mW•sec/sq cm	MPN/100 mL	MPN/100 mL	MPN/100 mL	MPN/100 mL
Influent	0	1.9×10^4	1.8×10^4	4.9×10^4	7.2×10^3
A	30	<2	<2	<2	<2
C	90	<2	<2	<2	<2
E	150	<2	<2	<2	<2

* Geometric mean of two discrete samples

Section 6

MONTGOMERY WATSON

SECTION 6

VIRUS INACTIVATION RESULTS AND DISCUSSION

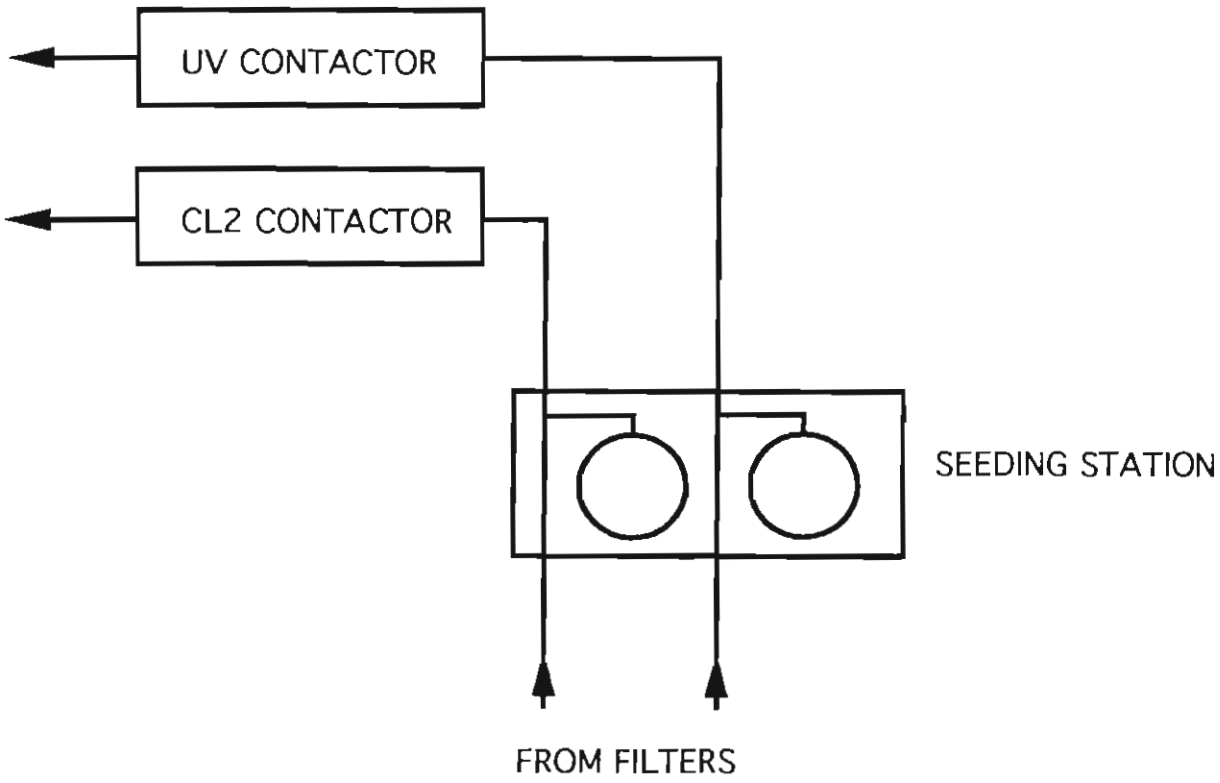
The California wastewater reclamation criteria requires a reduction in total coliform to ≤2.2 MPN/100 mL for irrigation of food crops and discharge to recreational impoundments. Studies have demonstrated that chlorination of wastewater treated in conformance with the California State Wastewater Reclamation Criteria (Title 22) requirements provides at least 4-log inactivation of seeded poliovirus. To demonstrate that UV radiation can achieve microbial inactivation "equivalent" to chlorine disinfection requires that 4-log inactivation of seeded poliovirus be achieved at the UV dose which meets the ≤2.2 MPN/100 mL total coliform requirement. The chlorine and UV doses required to achieve 4-log inactivation of polio virus seeded into the EVMWD Regional Plant filtered secondary effluent were determined from side-by-side disinfection studies performed at bench-scale and at full-scale. The bench-scale studies were performed in order to maintain flexibility in the applied doses and contact time and to see if the bench-scale data could reliably predict full-scale plant performance. For the full-scale studies, a continuous feed of poliovirus stock solution was supplied to the filtered secondary effluent upstream of the chlorine and UV contactors as shown in Figure 6-1. MS2 bacteriophage seedings were also performed at bench-scale and full-scale as a calibration for the SPSS calculated UV doses.

CHLORINE DISINFECTION RESULTS FOR POLIO VIRUS

The bench-scale chlorine disinfection studies were not successful because the stock polio virus supplied by Dr. Gerba's laboratory exerted an appreciable chlorine demand which interfered with an accurate determination of the chlorine dose required to achieve 4-log inactivation of the polio virus. The demand was caused by a freon extraction step performed to extract organic matter and lipids from the stock solution. This problem did not occur at full-scale because the large dilution of the feed stock solution in the full-scale plant did not produce a measurable chlorine demand.

Polio Results Obtained From Full-Scale Experiments

The filtered secondary effluent was analyzed for indigenous poliovirus on July 7, 1993 and August 3,1993 and both samples were below the assay detection limit of <1 pfu/100 L. The log inactivation of poliovirus at full-scale was determined by conducting five seeding



FULL-SCALE VIRUS SEEDING SCHEMATIC

FIGURE 6-1

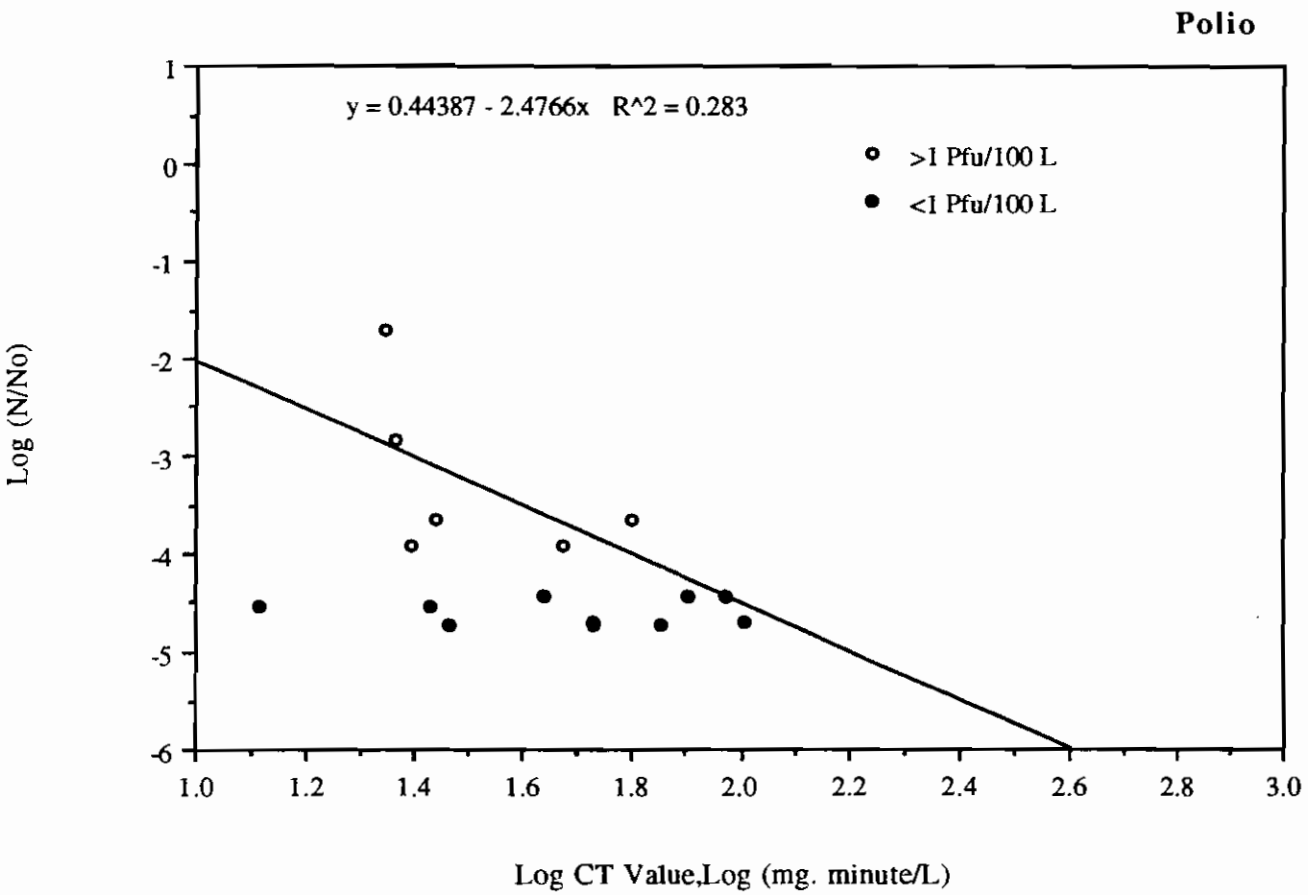
experiments between the period of July 7, 1993 and September 29, 1993. A detailed discussion of the seeding protocol is provided in Section 3. The concentration of free chlorine and poliovirus was measured in samples collected at various locations within the chlorine contactor as shown in Figure 3-7. Contact times and Ct values for each sampling location were calculated in accordance with the equations provided in Table 5-3. Only samples collected at 10 feet from the contactor inlet had measurable concentrations of poliovirus. Samples collected from 20, 30, 40, 50, and 110 feet from the contactor inlet were all <1 pfu/100 L with the exception of a sample collected at the 30 foot interval for the experiment conducted on July 7, 1993 which had a measured density of 6.0 pfu/100 mL.

A log inactivation plot based on the measured poliovirus data is presented in Figure 6-2. The data gives an estimated Ct value of 63 mg/L•min to obtain 4-log inactivation of poliovirus. This Ct value is slightly higher than the estimated 43 mg/L•min value required to achieve compliance with the ≤2.2 MPN/100 ml total coliform requirement obtained for the first channel sampling location. A similar CT value (50 mg/L•min) has been calculated for total coliform inactivation in a filtered nitrified wastewater disinfected with free chlorine using Selleck's model (Roberts *et al.*, 1980).

UV DISINFECTION RESULTS FOR POLIO VIRUS

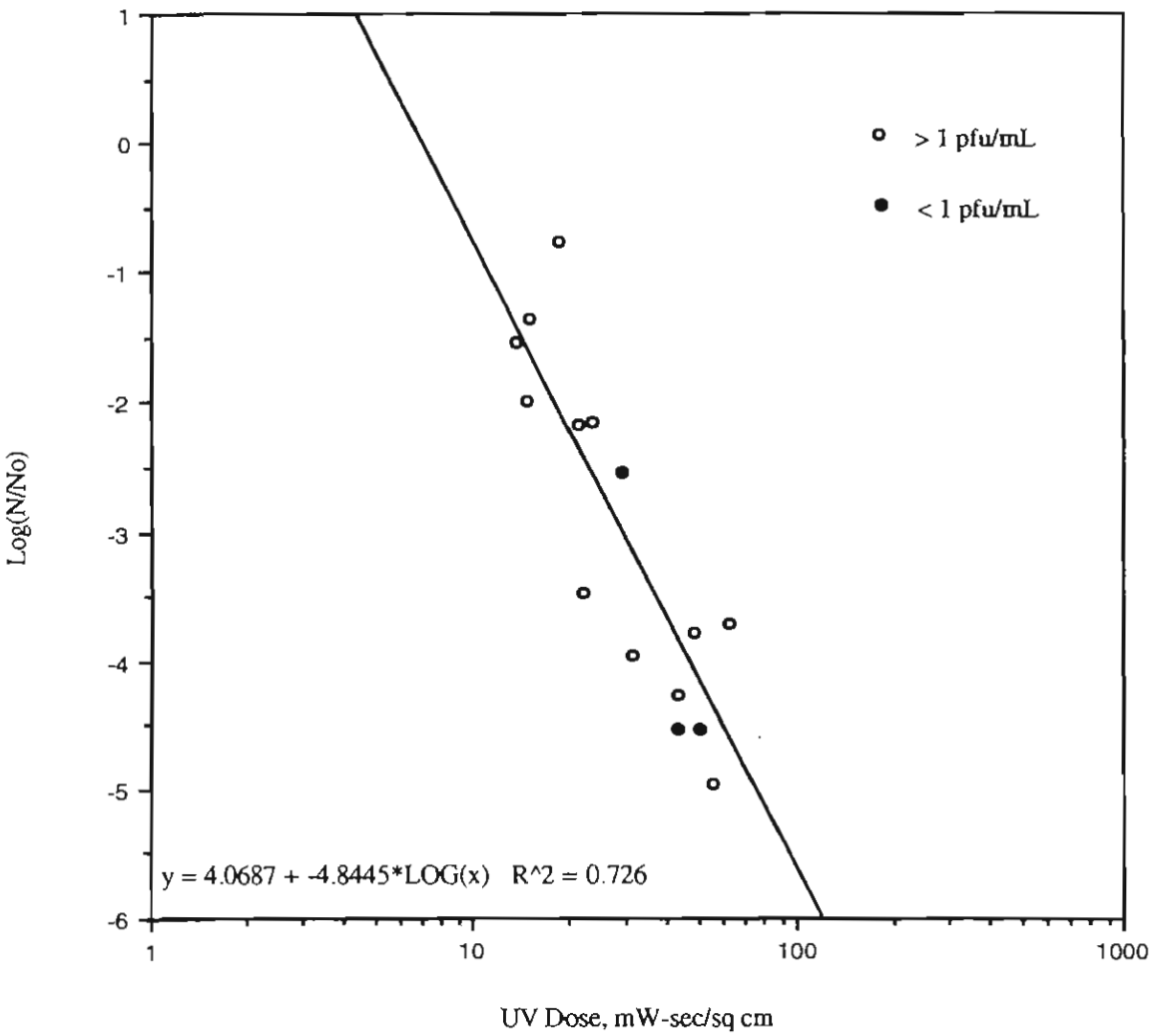
Polio Results Obtained From Bench-Scale Experiments

The log inactivation of poliovirus at bench-scale was determined by conducting five seeding experiments between the period of March 2, 1993 and August 4, 1993. Data from Run 7 and Run 8 were not utilized for the following reasons. The seeded influent concentration measured for Run 7 was suspect because it was more than a log below the concentration expected by calculation and was also a log lower than the control which was obtained using the same stock and dilution factor. Data from Run 8 was not utilized because complete inactivation of the seeded MS2 bacteriophage for the third, fourth, and fifth UV doses prevented an accurate calibration of the SPSS model calculated UV dose based upon the MS2 collimated beam calibration curve. The data from the three remaining experiments are presented in Figure 6-3. The 4-log inactivation dose is estimated to be 46 mw•sec/sq cm. This value is close to the 27 to 40 mw•sec/sq cm range reported in the literature (Chang, 1985; Harris, 1987; Wilson, 1992).



FULL-SCALE INACTIVATION OF POLIO VIRUS AS A FUNCTION OF CHLORINE CONTACT TIME

FIGURE 6-2



BENCH-SCALE INACTIVATION OF POLIO VIRUS

FIGURE 6-3

Polio Results Obtained From Full-Scale Experiments

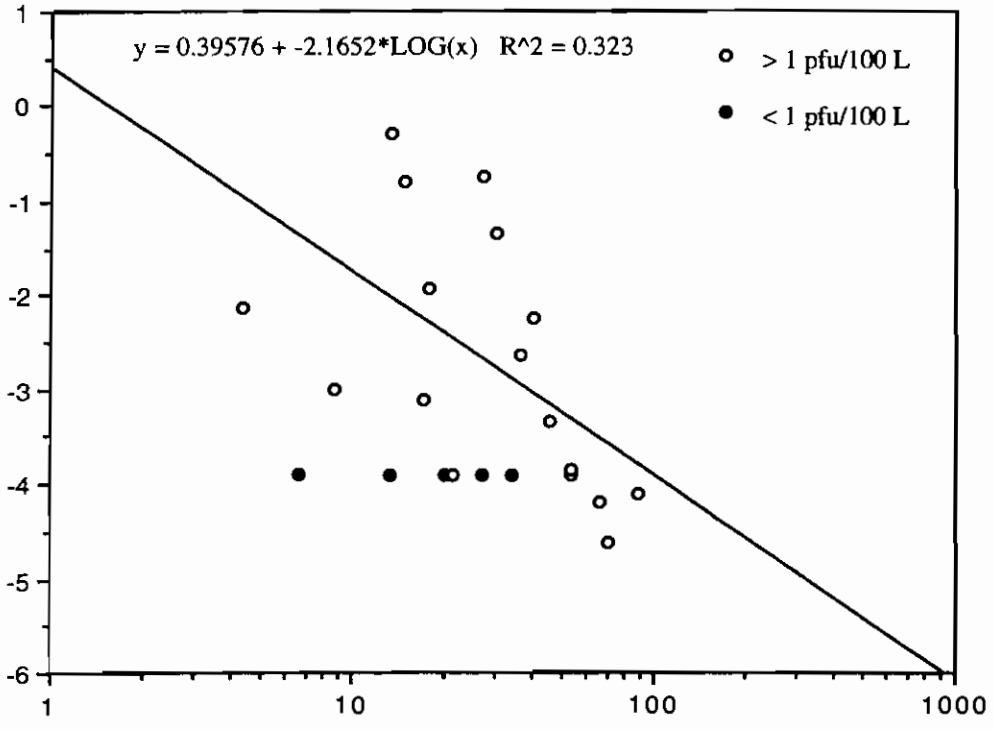
The log inactivation of poliovirus at full-scale was determined by conducting five seeding experiments between the period of July 7, 1993 and September 29, 1993. For the full-scale experiment performed on August 10, 1993, "control" samples were collected immediately after each UV bank when the UV lamps were not operating. These samples were analyzed for poliovirus and compared with the concentrations measured in the influent to the UV system. This control data, summarized in Figure 5-5 demonstrates that no appreciable loss of poliovirus was occurring due to adherence to the walls of the UV reactor. The data from full-scale experiments are presented in Figure 6-4. The 4-log inactivation dose is estimated to be 107 mw•sec/sq cm. If the two data points obtained at UV doses less than 10 mW•sec/sq cm are excluded from the regression (as was done with the bacterial inactivation data), the 4-log inactivation dose is estimated to be 68 mW•sec/sq cm. An inactivation lag is not apparent in Figure 6-4, but omission of these two data points should be considered when comparing the UV inactivation doses for the virus and the bacterial organisms in order to minimize the potential impact of experimental bias by comparing different dose ranges.

Comparison of UV Polio Inactivation Doses

Table 6-1 summarizes the 4-log polio inactivation doses obtained at bench-scale and at full-scale. For the full-scale data, the UV dose is presented based on the SPSS model corrected for lamp fouling using the fouling curve. The 95% confidence interval for each 4-log inactivation dose is also presented in Table 6-1 in parentheses next to each reported dose. The confidence interval was obtained by plotting the 95% confidence banks for the true mean of the Y variable (log N/No) and using the linear regression to calculate the UV dose interval corresponding to this inactivation interval. Comparison of the UV dose confidence intervals indicates no signficant difference in the 4-log inactivation doses obtained at bench-scale and at full-scale.

MS2 BACTERIOPHAGE

An MS2 seeding was performed with every bench-scale experiment. The lamps in the bench-scale reactor were cleaned prior to these experiments to remove any deposits on the quartz sleeves and insure that the lamps were not fouled. The inactivation data obtained from these seeding experiments were plotted as a function of the SPSS calculated dose to



FULL-SCALE UV INACTIVATION OF POLIO VIRUS

FIGURE 6-4

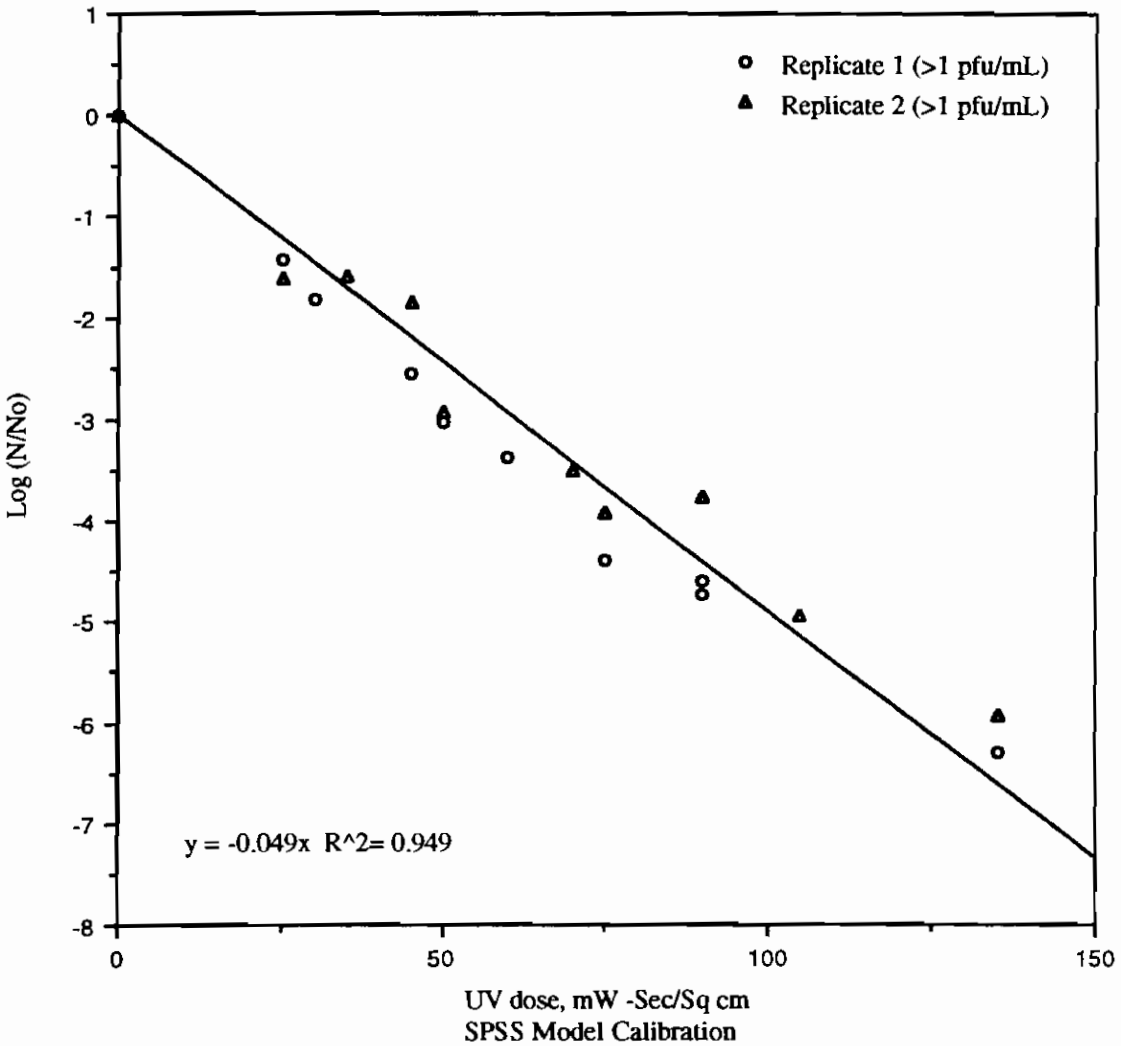
TABLE 6-1

UV DOSE TO ACHEIVE 4 LOG INACTIVATION OF POLIO VIRUS

Organism	Bench-scale SPSS dose corrected by MS2 calibration 3 runs		Full-scale SPSS dose corrected by fouling curve 5 runs	
	Mean	Confidence Interval	Mean	Confidence Interval
Polio virus	46	(33 - 64)	68	(41 - 113)

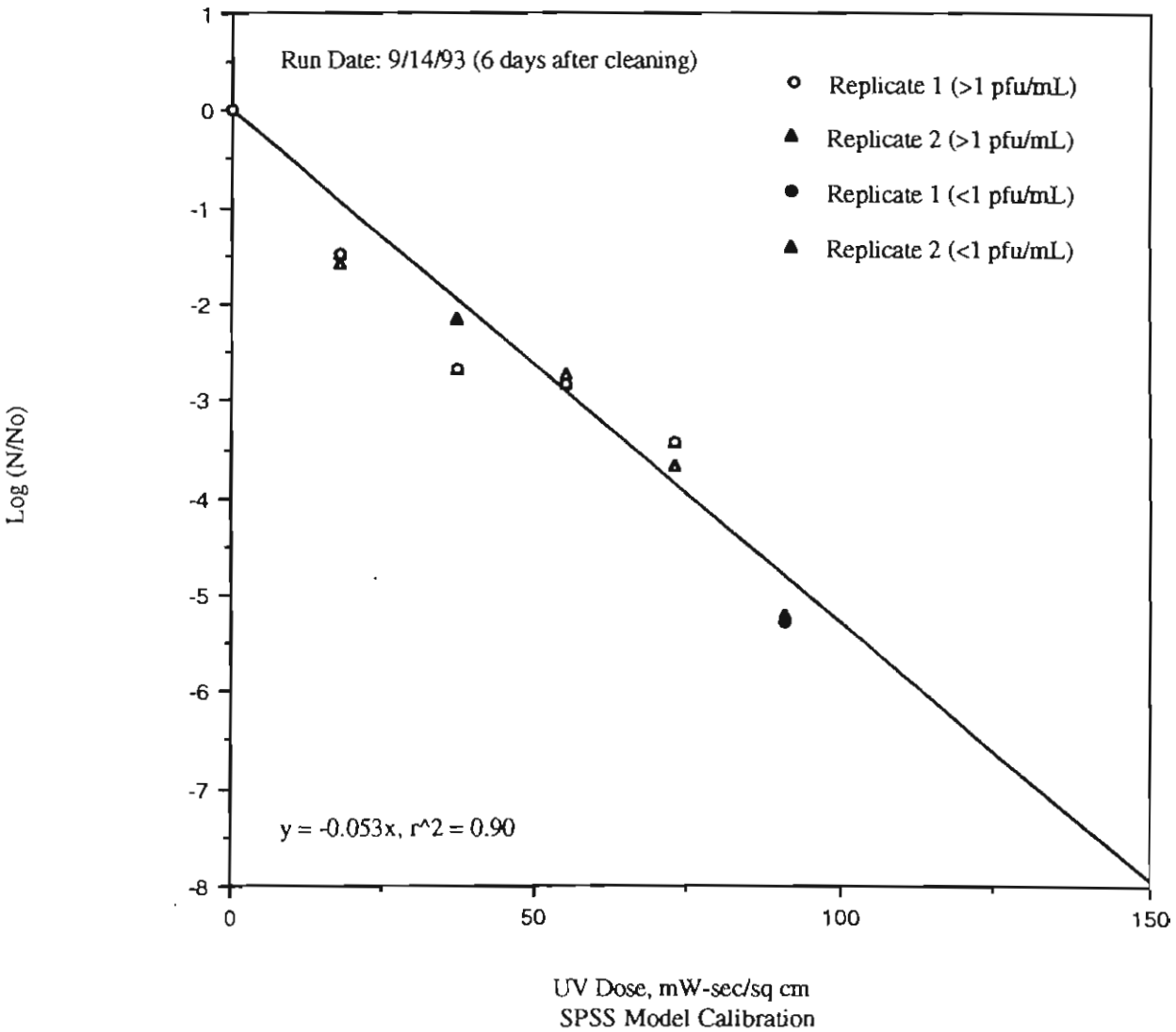
All doses are in mW•sec/sq cm

obtain a bench-scale dose response curve as shown in Figure 6-5. Two full-scale MS2 seedings were performed six days after the lamps were cleaned in order to obtain a full-scale dose response curve as shown in Figure 6-6. The regressions obtained for these two curves are almost identical indicating that the SPSS model is equally accurate in calculating the UV doses for the bench-scale and full-scale reactors. Comparison of these regression equations with the collimated beam regression equation indicates that the bench-scale SPSS calculated dose overestimates the "true" dose by 12% and the full-scale SPSS calculated dose overestimates the "true" dose by 4% when the lamps have not experienced any fouling.



MS2 BACTERIOPHAGE INACTIVATION AS A FUNCTION OF SPSS CALCULATED UV DOSE FOR THE BENCH-SCALE REACTOR WITH NO LAMP FOULING

FIGURE 6-5



MS2 BACTERIOPHAGE INACTIVATION AS A FUNCTION OF SPSS CALCULATED UV DOSE FOR THE FULL-SCALE REACTOR WITH MINIMAL LAMP FOULING

FIGURE 6-6

Section 7

MONTGOMERY WATSON

SECTION 7

DISINFECTION BY-PRODUCTS AND EFFLUENT TOXICITY

The safe use of a disinfectant is demonstrated by the disinfectant's inability to produce significant concentrations of mutagenic or carcinogenic disinfection by-products or whole effluent bioassay toxicity in addition to the the disinfectant's ability to consistently inactivate disease causing microorganisms. Chlorine is recognized as an effective biocide, but has been implicated in the formation of carcinogenic trihalomethanes. The acute toxicity of total residual chlorine to aquatic life has also been well documented through laboratory toxicity testing of power plant and municipal wastewater effluents and dechlorination is usually necessary to eliminate acute or chronic toxic effects to the receiving waters after the point of discharge.

UV radiation is an attractive alternative to chlorine disinfection, because UV may be capable of achieving an equivalent degree of microbial inactivation with substantially reduced production of carcinogenic by-products and finished effluent toxicity. As demonstrated in Section 2, insufficient research on UV byproducts and UV treated effluent toxicity has been published to fully support the safe use of UV radiation as an alternative disinfectant. A complete characterization of disinfectant byproducts and bioassay toxicity for a given effluent is difficult to obtain due to the complex and diverse nature of the byproduct precursor material present in wastewater effluents. A reduction in the carcinogenicity or toxicity of an effluent when switching from chlorination to UV radiation can only be demonstrated by conducting a controlled side-by-side comparison of the chemical composition and bioassay toxicity of an effluent prior to disinfection and immediately following disinfection with chlorine or UV radiation. This Section summarizes the results of such controlled testing performed with EVMWD's Regional Plant filtered secondary effluent.

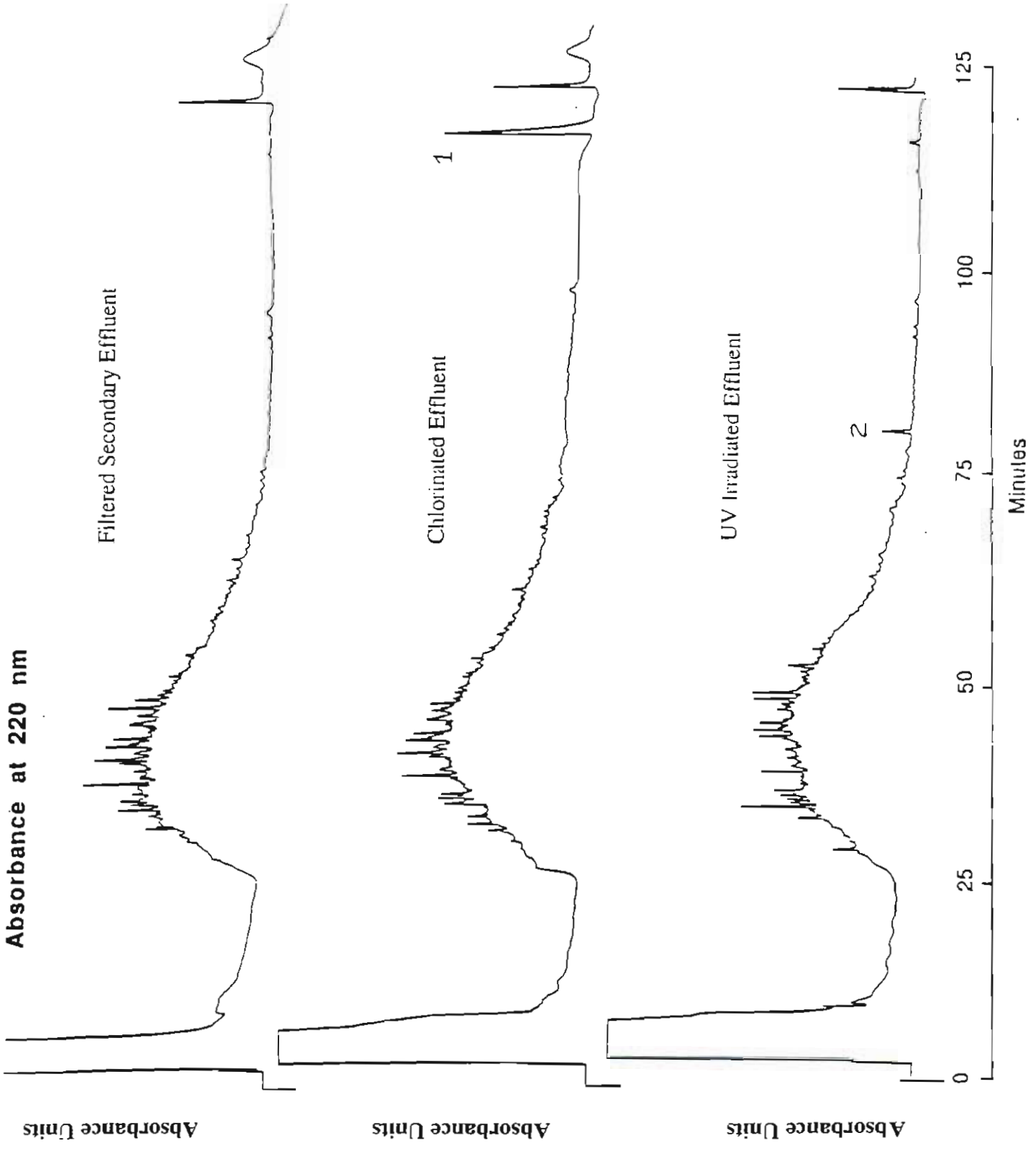
DISINFECTION BY-PRODUCT CHARACTERIZATION

Filtered secondary effluent was collected from the Regional Plant for DBP experiments as summarized in Table 3-2. Sample collected on January 19, 1993 was immediately returned to Montgomery Watson's Research Facility and disinfected at bench-scale with a UV dose of 300 mW•sec/sq cm and a chlorine dose of 10 mg/L and a 2-hour contact time. The filtered secondary effluent, the chlorinated filtered secondary effluent, and the UV

irradiated filtered secondary effluent samples were analyzed by GC/MS and LC/MS without any preconcentration techniques. The GC/MS analysis was performed in accordance with EPA Method 5030/8260 with identification of the 10 highest non-target compound peaks through mass spectral library matching. The LC/MS analysis was performed as described in Section 3. No unique peaks were detected in the UV irradiated sample. The chlorinated sample demonstrated production of approximately 75 mg/L of trihalomethanes.

The experiment was repeated on a sample collected on May 4, 1993. This time, to maximize the probability of detecting UV byproducts, a much higher dose of UV radiation was applied, the samples were preconcentrated prior to analysis, and a HPLC/UV chromatographic profile was obtained as an initial screening technique prior to performing more detailed mass spectrometry work on isolated chromatographic fractions. The applied UV dose was 2800/sq cm. Following lyophilization, each sample was redissolved in HPLC-grade water and centrifuged to remove visible particulates. Half of each concentrate was analyzed by direct injection HPLC. The other half of each concentrate was acidified and extracted with ethyl acetate to enhance HPLC analysis of the less polar compounds. The centrifugation pellets were also extracted with ethyl acetate for analysis by HPLC. Details of the lyophilization, additional preparation, and HPLC chromatographic conditions are described in Section 3.

Figures 7-1 and 7-2 show the chromatographic profiles obtained for the three samples analyzed by direct injection at UV absorbances of 220 nm and 280 nm. The majority of the compounds are present in the polar solvent front of the chromatogram. Although the peaks are poorly resolved, there are distinct differences in the profiles for the three samples. In both figures, a unique UV peak appears (labeled Peak 2) at a retention time of approximately 85 minutes. This portion of the chromatogram corresponds to mid-polarity compounds. There is also a unique chlorinated peak (labeled Peak 1) occurring in the non-polar region of the chromatogram. Figures 7-3 and 7-4 show the chromatographic profiles obtained for the ethyl acetate extracts of the three samples. Considerably fewer peaks are present in the polar solvent front as expected due to the affinity of polar compounds for the aqueous phase. Peak 1 and Peak 2 are no longer apparent in these extracts. Figures 7-5 and 7-6 represent the chromatographic profiles obtained for the ethyl acetate extracts of the pelleted particulates removed in the centrifugation process at UV absorbances of 220 nm and 280 nm. Comparison of these chromatograms with Figures 7-3 and 7-4 show that



REVERSED-PHASE HPLC OF LYOPHILIZED AND REDISSOLVED FILTERED SECONDARY EFFLUENT DISINFECTED AT BENCH-SCALE (ABSORBANCE AT 220 nm)

FIGURE 7-1

REVERSED-PHASE HPLC OF LYOPHILIZED AND REDISSOLVED FILTERED SECONDARY EFFLUENT DISINFECTED AT BENCH-SCALE (ABSORBANCE AT 280 nm)

FIGURE 7-2

REVERSED-PHASE HPLC OF EXTRACTS OF THE CENTRIFUGATION PELLETS FROM LYOPHILIZED AND REDISSOLVED FILTERED SECONDARY EFFLUENT DISINFECTED AT BENCH-SCALE (ABSORBANCE AT 280 nm)

FIGURE 7-6

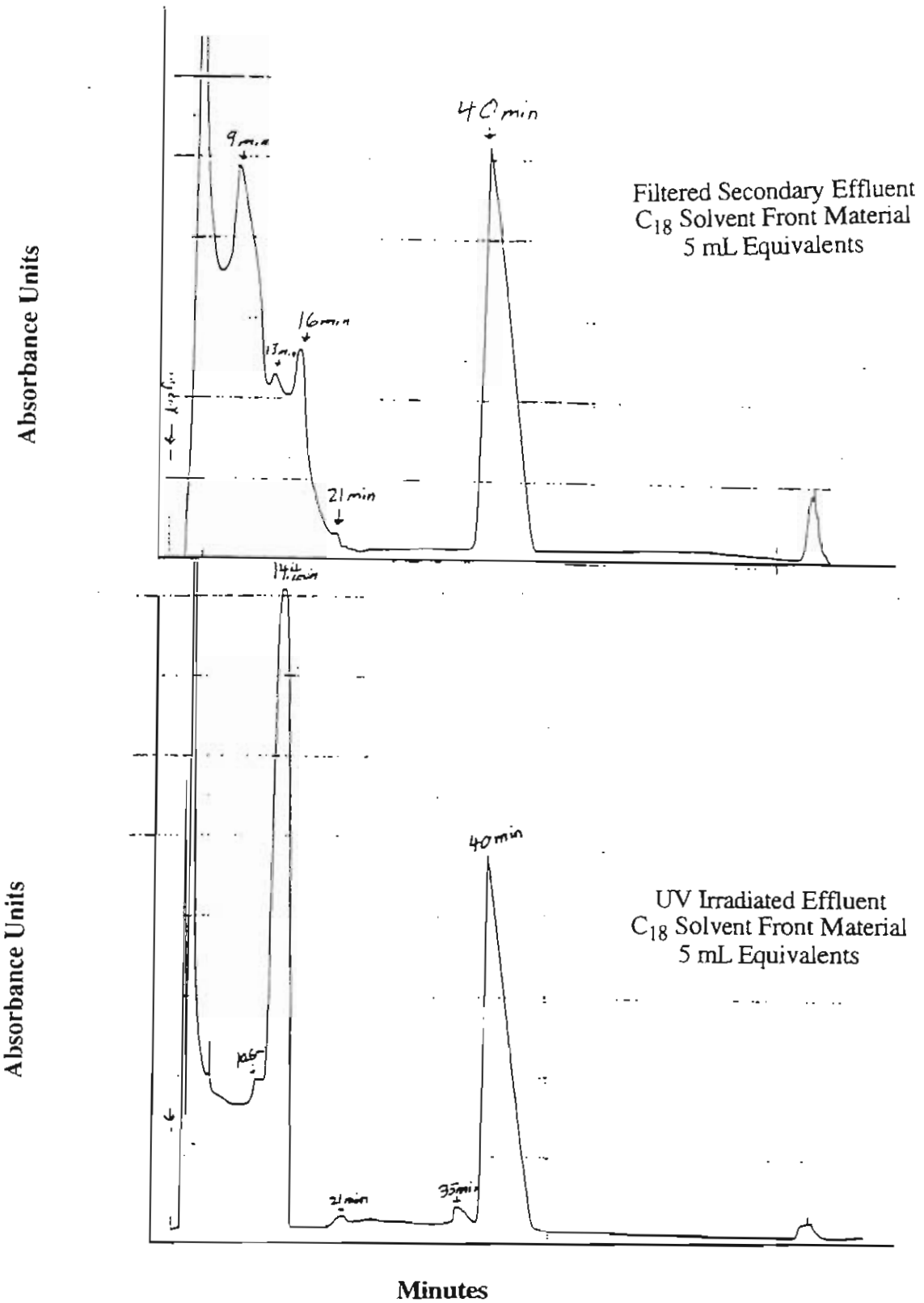
many additional non-polar compounds appear in the righthand side of the chromatographic profiles indicating that the majority of these compounds appear to be particle associated.

To enhance the resolution of compounds present in the polar solvent front, the concentrated samples were chromatographed again employing mixed function columns containing anion or cation exchange resins. For the acidic polar compounds, a unique UV by-product peak was detected at an elution time of 35 minutes as shown in Figure 7-7. There also may have been compound transformations occurring between elution times of 9 and 14 minutes, but these transformations also occurred in the chlorinated sample. For the basic polar compounds, a unique UV by-product peak was detected at an elution time of 9 minutes, but no basic polar compounds were detected in the nondisinfected or chlorinated sample. These chromatograms are presented in Figure 7-8.

Aliquots of the filtered secondary effluent collected and disinfected on May 4, 1993 were also analyzed by closed-loop stripping/GC-MS analysis. The closed-loop stripping process is an alternative preconcentration technique which should result in less loss of volatile compounds than the lyophilization process. Two unidentified peaks (Unknown scan #1261 and #1297) were identified in both the chlorinated and UV irradiated samples and several halogenated volatile organics were also identified in the chlorinated sample. Additional halogenated compounds were probably also present in the chlorinated sample, but were not well identified by this method because of interference from the carbon disulfide solvent used in the preconcentration technique. A summary of the compounds identified in the filtered secondary effluent, chlorinated filtered secondary effluent, and UV irradiated filtered secondary effluent from the GC-MS analyses is provided in Table 7-1.

In the attempt to characterize UV Peak 2, additional sample was needed. On June 16, 1993, additional filtered secondary effluent was collected from the Regional Plant and irradiated at the Montgomery Watson Research Laboratory. This sample was preconcentrated utilizing solid-phase extraction with Mega Bond Elut C_{18} sorbent (Varian, Harbor City, CA) instead of lyophilization. Details of this preconcentration technique are provided in Section 3. The same unique UV Peak 2 was detected at a retention time of approximately 80 minutes.

Attempts to identify Peak 2 were not successful. A GC-MS analysis of the reversed-phase HPLC purified single peak failed to yield any clear molecular ion(s), indicating that the material may not have been volatile or stable enough for GC. Subsequent analysis by



MIXED-PHASE HPLC OF ACID POLAR C_{18} SOLVENT FRONT MATERIAL FROM FILTERED SECONDARY EFFLUENT DISINFECTED AT BENCH-SCALE

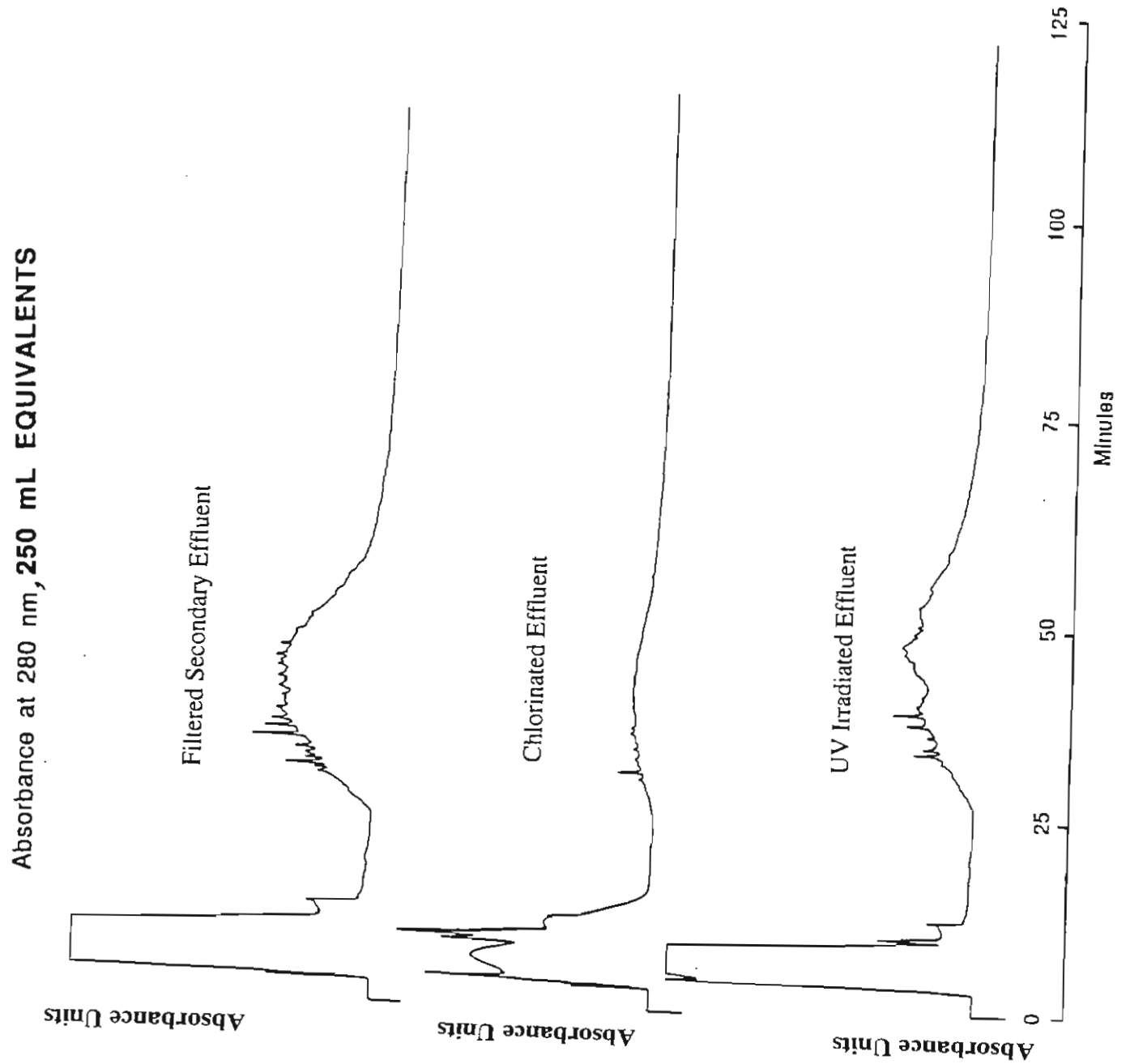
FIGURE 7-7

TABLE 7-1

BY-PRODUCTS IN EVMWD FILTERED SECONDARY EFFLUENT BEFORE AND AFTER DISINFECTION.

Compounds Detected	Filtered Effluent	Chlorinated Effluent	UV Effluent
	(µg/L)	(µg/L)	(µg/l)
Chloroform[1]	2.7	21*	2.9†
Dibromochloromethane[1]	0.9	22*	0.8†
Dichlorobromomethane[1]	1.1	27*	1.0†
Bromoform[1]	<0.5	2.7*	<0.5†
1,1,1-Trichloropropanone[2]	Not Detected	0.2§	Not Detected¥
Unresolved scan #1261[2]	Not Detected	0.1§	0.066¥
Unresolved scan #1267[2]	Not Detected	0.096§	0.079¥
Acetaldehyde[3]	<5	21¶	7¶
Formaldehyde[3]	<5	24¶	8¶
Glyoxal[3]	<5	5¶	<5¶
M-Glyoxal[3]	<5	<5¶	<5¶

*Chlorine = 9.8 mg/L dose and 2-hr contact time
†UV = 300 mW•sec/sq cm
§Chlorine = 10 mg/L dose and 2-hr contact time
¥UV = 2800 mw•sec/sq cm
1=Purge and Trap GC/MS (EPA Method 5030/8260)
2=Closed-Loop Stripping GC/MS (Standard Method 6040, 18th ed, 1992)
¶=Samples collected from full-scale reactors (UV dose-188 mW•sec/sq cm)

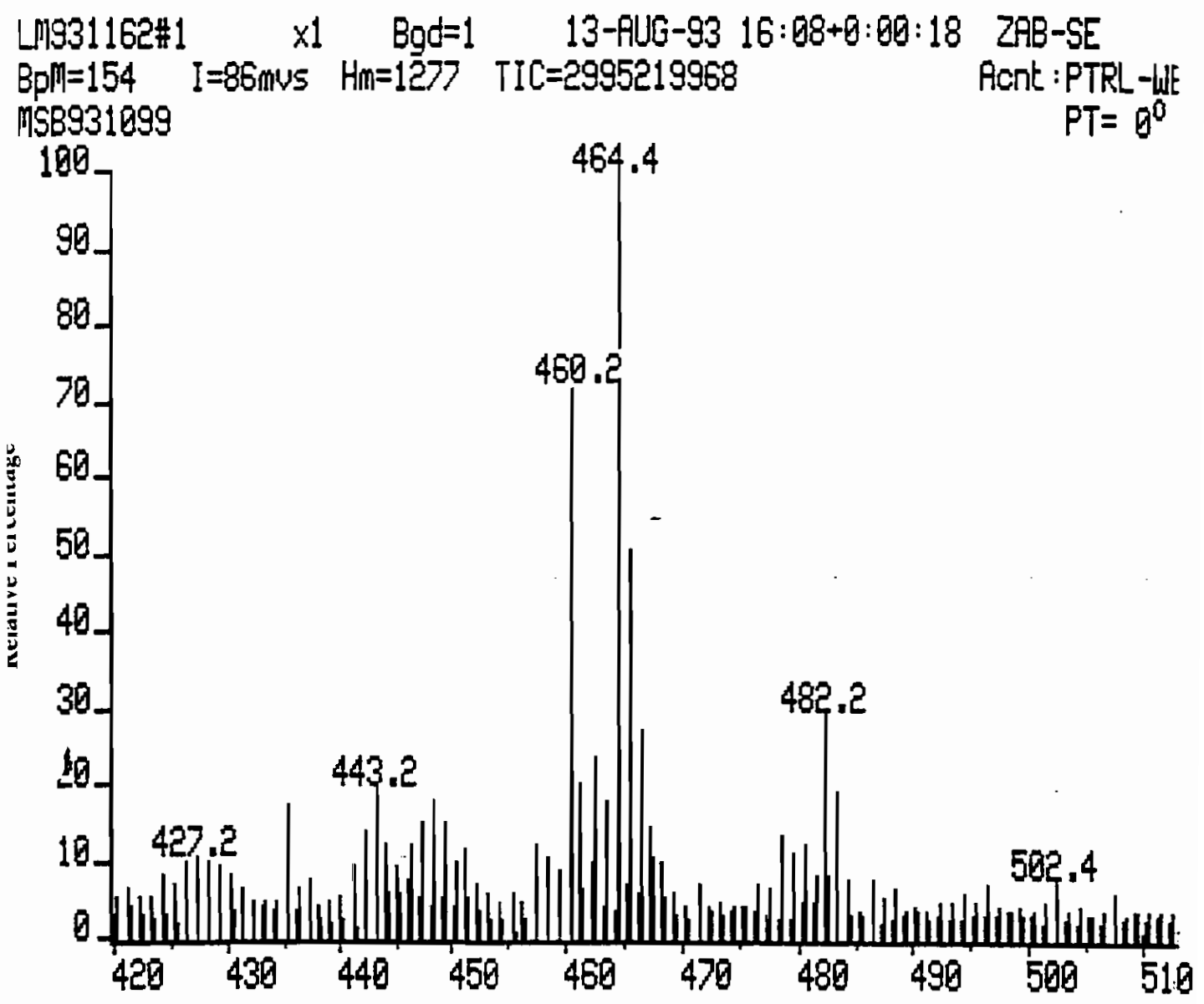


REVERSED-PHASE HPLC OF LYOPHILIZED AND REDISSOLVED FILTERED SECONDARY EFFLUENT DISINFECTED AT FULL-SCALE (ABSORBANCE AT 280 nm)

FIGURE 7-11

REVERSED-PHASE HPLC OF LYOPHILIZED AND REDISSOLVED FILTERED SECONDARY EFFLUENT IRRADIATED AT BENCH-SCALE

FIGURE 7-12



FAST ATOM BOMBARDMENT-MASS SPECTRA OF ISOLATED PEAK 1 FROM FILTERED SECONDARY EFFLUENT CHLORINATED AT BENCH-SCALE

FIGURE 7-13

TABLE 7-2

POSSIBLE ELEMENTAL COMPOSITIONS OF PEAK 1 COMPONENT WITH MOLECULAR MASS OF 464.1272800 D

Single Mass Input Page: 1-1

M/E	C 12	H	O	N	S	P	PPM	DBE	ACC. MASS
464	28	23	0	3	1	1	-16.7	19.5	464.1350331
	27	22	0	4	0	2	-10.1	20.0	464.1319737
	27	21	0	4	1	1	10.4	20.0	464.1224571
	26	20	0	5	0	2	17.0	20.5	464.1193976
	23	24	0	5	1	2	9.7	15.5	464.1227696
	29	24	1	1	0	2	-13.0	19.5	464.1333164
	29	23	1	1	1	1	7.5	19.5	464.1237998
	28	22	1	2	0	2	14.1	20.0	464.1207403
	25	26	1	2	1	2	6.8	15.0	464.1241123
	27	20	2	4	1	0	-7.4	20.0	464.1306979
	23	23	2	5	1	1	-8.0	15.5	464.1310104
	29	22	3	1	1	0	-10.3	19.5	464.1320406
	28	21	3	2	0	1	-3.7	20.0	464.1289812
	28	20	3	2	1	0	16.8	20.0	464.1194645
	25	25	3	2	1	1	-10.9	15.0	464.1323531
	24	24	3	3	0	2	-4.3	15.5	464.1292937
	24	23	3	3	1	1	16.2	15.5	464.1197771
	21	28	3	3	1	2	-11.6	10.5	464.1326657
	20	26	3	4	1	2	15.5	11.0	464.1200896
	22	28	4	1	1	2	12.6	10.5	464.1214323
	24	22	5	3	1	0	-1.6	15.5	464.1280179
	23	21	5	4	0	1	5.0	16.0	464.1249585
	20	25	5	4	1	1	-2.3	11.0	464.1283304
	19	24	5	5	0	2	4.3	11.5	464.1252710
	16	28	5	5	1	2	-2.9	6.5	464.1286430

TABLE 7-3

POSSIBLE ELEMENTAL COMPOSITIONS OF PEAK 1 COMPONENT WITH MOLECULAR MASS OF 464.3431200 D

Single Mass Input Page: 1-1

M/E	C 12	H	O	N	S	P	PPM	DBE	ACC. MASS
464	27	50	0	2	0	2	-3.9	5.0	464.3449268
	27	49	0	2	1	1	16.6	5.0	464.3364102
	28	42	1	5	0	0	9.0	10.5	464.3389364
	25	46	1	5	1	0	1.7	5.5	464.3423083
	30	44	2	2	0	0	6.1	10.0	464.3402791
	27	48	2	2	1	0	-1.1	5.0	464.3436510
	26	47	2	3	0	1	5.4	5.5	464.3405916
	22	50	2	4	0	2	4.8	1.0	464.3409041
	26	46	4	3	0	0	-12.3	5.5	464.3488324
	25	44	4	4	0	0	14.8	6.0	464.3362564
	22	49	4	4	0	1	-13.0	1.0	464.3491450
	22	48	4	4	1	0	7.5	1.0	464.3396283
	21	47	4	5	0	1	14.1	1.5	464.3365689
	27	46	5	1	0	0	11.9	5.5	464.3375990
	24	50	5	1	1	0	4.6	0.5	464.3409710
	23	49	5	2	0	1	11.2	1.0	464.3379116

results are presented in Table 7-4. No aldehydes were detected in the filtered secondary effluent and significantly higher amounts of formaldehyde, acetaldehyde, and glyoxyl are formed in the chlorinated sample than the UV irradiated sample. The high levels of aldehydes detected in the chlorinated effluent are in agreement with the findings of a potable water survey sponsored by the USEPA's Office of Drinking Water and the Association of Metropolitan Water Agencies in 1988. The survey, performed by the Metropolitan Water District of Southern California and Montgomery Watson, resulted in data suggesting that when a utility's water quality and treatment practices produce a high level of THMs, they can potentially produce a high level of formaldehyde (Krasner et. al, 1989) .

WHOLE EFFLUENT TOXICITY TESTING

Samples of the filtered secondary effluent, chlorinated filtered secondary effluent, and UV irradiated filtered secondary effluent collected from the Regional Plant on November 17, 1993 were analyzed for whole effluent toxicity (WET). The following acute and chronic toxicity tests, as specified in the California Inland Surface Waters Plan and the Regional Plant's NPDES permit, were performed:

1. Seven-day, chronic, fathead minnow (*Pimephales promelas)* static renewal, larval survival and growth test;

2. Seven-day (three-brood), chronic, *Ceriodaphnia dubia*, static renewal, survival and reproduction test;

3. Four-day, chronic, *Selenastrum capricornutum,* static, growth test;

Chronic toxicity is expressed as TUc which is calculated from the lowest dilution of the effluent sample which produces an observable effect to some attribute of the test organism. The attributes measured are survival and growth for fathead minnow larvae and *Ceriodaphnia* and growth for *Selanastrum* algae. A statistical comparison of the attribute values obtained for a population of ten organisms at each sample dilution level is performed to determine the minimum dilution at which the no observable effect concentration (NOEC) is achieved. The TUc is then computed as 100/NOEC. An exceedance of 1.00 for the TUc is defined as evidence of chronic toxicity. The toxicity -based permit limit is then determined by dividing a TUc of 1.00 by the dilution factor by which the effluent is diluted in the receiving water. Since EVMWD's Regional Plant is administered under California's Inland Surface Waters Plan, adjustment of the TUc by a dilution factor is not allowed due

TABLE 7-4

SUMMARY OF ALDEHYDE ANALYSES

Parameter	Filtered Secondary Effluent (µg/L)	Chlorinated Effluent (µg/L)	UV Effluent (µg/L)
Acetaldehyde	<5	21	7
Formaldehyde	<5	24	8
Glyoxal	<5	5	<5
M-Glyoxal	<5	<5	<5

to the arid conditions existing within the State. Therefore, a TUc value greater than 1.00 is considered evidence of chronic toxicity and an exceedance of the chronic toxicity effluent limitation. Consistent exceedance of the toxicity effluent limit results in the requirement to conduct a toxicity reduction evaluation (TRE) and reduce toxicity once the source of toxicity is identified. The definition of consistent exceedance is not yet defined in the NPDES permit for the EVMWD Regional Plant.

The chronic toxicity test data is summarized in Table 7-5. No chronic toxicity was evident for the fathead minnow or *Ceriodaphnia* for the undisinfected filtered secondary effluent or the UV irradiated filtered secondary effluent. The No Observable Effect Concentration (NOEC) for survival and growth occurred at 100% effluent concentration resulting in a calculated chronic toxicity value (TUc) of 1.00. Chronic toxicity was observed for the chlorinated filtered secondary effluent for the *Ceriodaphnia* growth bioassay. The reproduction NOEC for the chlorinated sample was 56.00%, resulting in a calculated TUc of 1.79. The *Selanastrum* chronic toxicity tests were inconclusive because of a quality control problem evidenced from the standard toxicant control test. Additional samples were collected from the full-scale plant on December 13, 1993 so the test could be repeated. The data indicate chronic toxicity for all three samples with a growth NOEC of 56% and a TUc of 1.79. Therefore, only the chlorination process appears to increase the chronic toxicity of the filtered secondary effluent as evidenced by the increased TUc value for the *Ceriodaphnia* growth bioassay. Enhanced chronic toxicity of wastewater effluent is frequently found after the chlorination process and it is most typically manifested as an increase in the TUc value for the *Ceriodaphnia dubia* growth bioassay.

Chronic toxicity data obtained from the Regional Plant's chlorinated filtered secondary effluent as part of their NPDES permit monitoring are summarized in Table 7-6. A sample collected in March, 1993 showed no chronic toxicity for any of the test organisms while a sample collected in June, 1993 showed chronic toxicity for *Ceriodaphnia* reproduction (TUc = 3.13), fathead minnow growth (TUc = 3.13), and fathead minnow survival (TUc = 3.13). Since no side-by-side data is available for the effluent prior to disinfection, it is difficult to determine if the chronic toxicity is formed during the chlorination process or was present in the effluent prior to disinfection. Acute toxicity data obtained from the Regional Plant's chlorinated filtered secondary effluent as part of their NPDES permit monitoring are summarized in Table 7-7. Bi-monthly static 96-hour acute survival testing of fathead minnows and *Ceriodaphnia* and bi-monthly static 96-hour acute growth of *Selanastrum* between February 1993 through August 1993 did not show any evidence of

TABLE 7-5

SUMMARY OF CHRONIC TOXICITY DATA OBTAINED FOR THIS STUDY

Parameter	Filtered Secondary Effluent		Chlorinated Effluent		UV Effluent	
	NOEC	TUc	NOEC	TUc	NOEC	TUc
Fathead Larvae Survival	100%	1.00	100%	1.00	100%	1.00
Fathead Larvae Growth	100%	1.00	100%	1.00	100%	1.00
Ceriodapnia Survival	100%	1.00	100%	1.00	100%	1.00
Ceriodapnia Reproduction	100%	1.00	56%	1.79	100%	1.00
Selanastrum Growth *	56%	1.79	56%	1.79	56%	1.79

Notes:

Based on a single sample collected on November 18, 1993

* *Selanastrum* was repeated with new sample collected on December 14, 1993

TABLE 7-6

SUMMARY OF CHRONIC TOXICITY DATA OBTAINED FOR NPDES PERMIT MONITORING OF CHLORINATED EFFLUENT

Parameter	March 1993		June 1993	
	NOEC	TUc	NOEC	TUc
Fathead Larvae Survival	100%	1.00	32%	3.13
Fathead Larvae Growth	100%	1.00	32%	3.13
Ceriodapnia Survival	100%	1.00	100%	1.00
Ceriodapnia Reproduction	100%	1.00	32%	3.13
Selanastrum Growth *	100%	1.00	100%	1.00

TABLE 7-7

SUMMARY OF ACUTE TOXICITY DATA OBTAINED FOR NPDES PERMIT MONITORING OF CHLORINATED EFFLUENT

Parameter	1993							
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
Fathead Minnow Survival in 100% Sample	100%	100%	95%	100%	100%	100%	90%	100%
Fathead Minnow Survival Inhibitory Concentration for 25% of population		>100%		>100%		>100%		>100%
Ceriodapnia Survival Inhibitory Concentration for 25% of Population		>100%		>100%		>100%		>100%
Selanastrum Growth Inhibitory Concentration for 25% of Population		>100%		>100%		>100%		74%

acute toxicity except for the August 1993 Selanastrum test which showed inhibitory growth of 25 percent of the population (IC25) at a 73.94 % concentration of the effluent. Monthly testing of the acute 96-hour fathead minnow survival between January 1993 and August 1993 always resulted in the absence of acute toxicity.

SUMMARY

The only disinfection by-products detected without sample preconcentration techniques were the trihalomethanes and these were primarily formed during the chlorination process. All other by-products were detected in preconcentrated samples. The closed-loop stripping technique concentrates the sample by a factor of approximately 40,000 and is most efficient for volatile and semi-volatile compounds although detection of trihalomethanes is compromised because of solvent interference from carbon disulfide. The HPLC peaks were obtained on lyophilized or precolumn concentrated samples concentrated by a factor of approximately 50.

The ammonia concentration in the Elsinore tertiary effluent was not measured during sample collection, but it is a nitrified and partially denitrified effluent and rarely contains more than 0.1 mg/L of ammonia. Therefore the chlorinated effluent consisted of free chlorine and enhanced production of chloroform and trihalomethanes is expected in the presence of free chlorine (White, 1986). This undoubtedly accounts for the high concentrations (approximately 75 mg/L) of THMs measured in the chlorinated effluent. No measurable THMs were produced in the UV irradiated effluent.

A unique mid-polarity UV by-product peak produced at an applied dose of approximately 2800 mW•sec/sq cm under bench-scale conditions was not found from UV irradiated sample collected from the full-scale plant. Failure to produce this UV by-product peak at full-scale was probably due either to the much lower UV dose of 188 mW•sec/sq cm applied at full-scale or the additional full-scale dilution of this compound to a concentration level below the analytical detection limit. The 2800 mW•sec/sq cm dose represents a much higher dose than the 100 to 140 mW•sec/sq cm dose range demonstrated to inactivate the target organisms. Attempts to identify this UV peak with low and high resolution FAB/MS were not successful. The apparent lack of significant UV byproducts is not unexpected due to the much lower molar absorption extinction coefficient of organic carbon bonds as compared with the

extinction coefficients for nitrogenous heterocyclic bases of the DNA/RNA nucleotides where UV inactivation occurs through pyrimidine dimerization. A unique chlorinated by-product peak was produced under bench-scale conditions of an applied chlorine dose of 10 mg/L and a 2-hour contact time. The peak was identified as two separate compounds with molecular weights of approximately 461.1 and 461.3 d. Further structural identification of the compounds was not performed.

Bioassay testing of the full-scale plant filtered secondary effluent, chlorinated filtered secondary effluent, and UV irradiated filtered secondary effluent indicated possible production of chronic toxicity from the chlorination process. This chronic toxicity was measured as a decline in the reproductive rate of Ceriodaphnia dubia. No chronic toxicity was evident from the UV irradiation process.

Section 8

MONTGOMERY WATSON

SECTION 8

OPERATION AND MAINTENANCE OF EFFECTIVE UV DOSE

The UV dose required to achieve 4-log inactivation of the target organisms and a total coliform density of ≤2.2 MPN/100 mL was discussed in Sections 5 and 6. Maintenance of this minimum UV dose at a full-scale facility is dependent upon continuously maintaining an effective combination of the average reactor UV intensity and exposure time within the UV reactor. The average reactor UV intensity is a function of the number of lamps, their configuration, their radiation output, lamp age, the transmittance of the quartz sleeve surrounding the lamp, the change in the quartz sleeve transmittance due to fouling caused by deposition of mineral and particulate material on the sleeves, and significant changes in the UV transmittance or particle characteristics of the effluent undergoing disinfection. The exposure time in the UV reactor can be calculated from the theoretical hydraulic detention time if the hydrodynamic conditions in the UV reactor are plug-flow and minimal axial dispersion (mixing in the direction of flow) occurs. This must be evaluated through tracer testing of the residence time distribution through the UV reactor.

MAINTAINING UV INTENSITY

Direct measurement of the average reactor UV intensity with UV sensors is not feasible because the sensors are only indicative of the intensity at their specific reactor locations and a sufficient number of sensors could not be mounted within the UV reactor to get an accurate estimation of the average UV intensity within the reactor. The sensors are also not an effective on-line method of determining UV intensity at specific locations because they are subject to rapid fouling and component failure which leads to inaccurate readings. These difficulties are demonstrated in Figure 8-1 which presents the intensity sensor readings obtained for the EVMWD Regional Plant UV system during several months of continuous operation. Of note is the fact that the UV intensity readings only returned to approximately 60 percent of their initial readings even after cleaning the lamps and correcting for the intensity loss expected due to lamp aging. The Figure also demonstrates the inability of the probes to provide any measurable intensity reading after > x months of operation presumably due to excessive fouling of the probes.

UV INTENSITY READINGS OBTAINED FOR EVMWD FULL-SCALE UV REACTOR

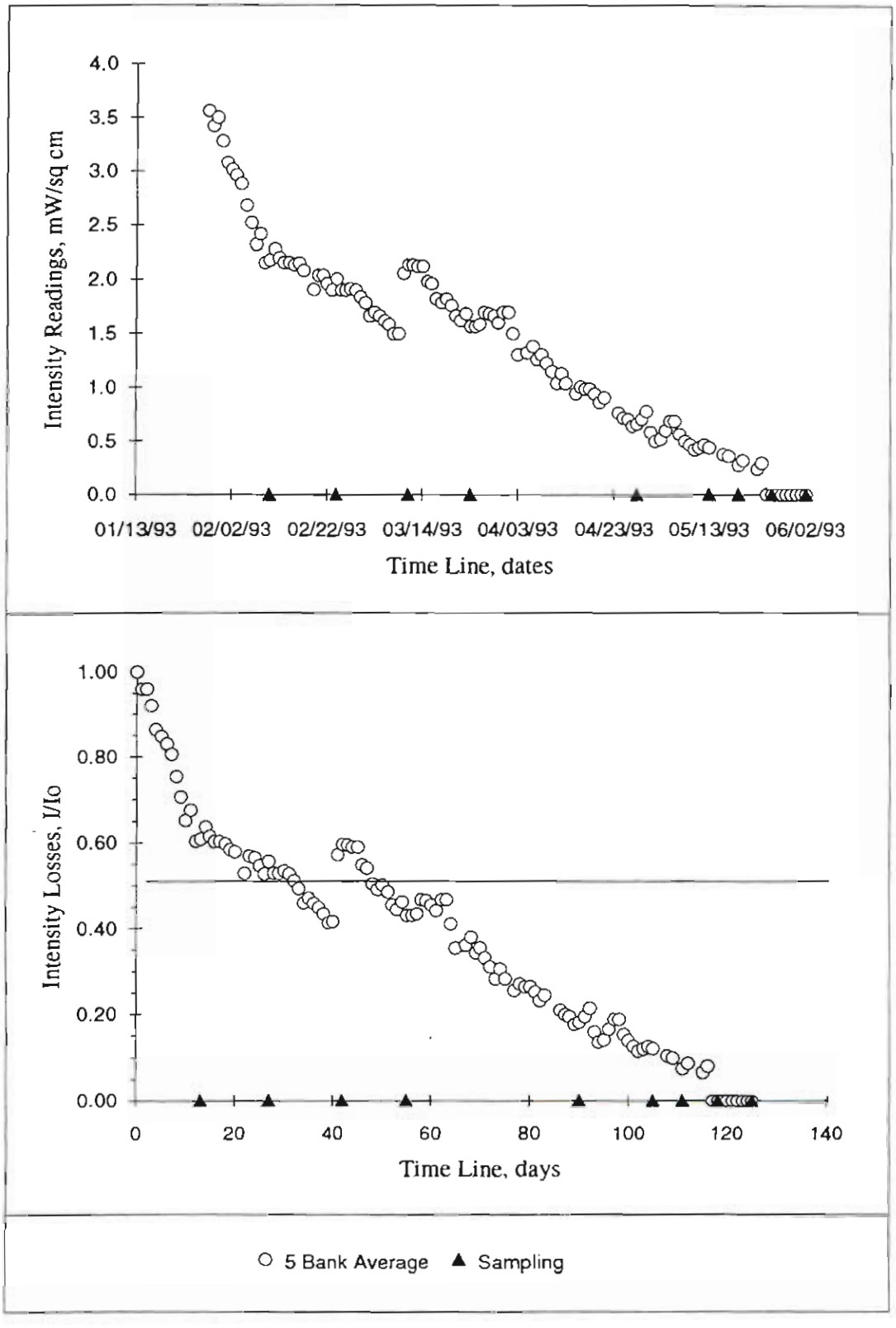


FIGURE 8-1

Due to the lack of an effective on-line measuring device for UV intensity, demonstration of the average reactor UV intensity over time is approximated from mathematical models which calculate the average UV intensity at any point within a particular reactor. These computer models calculate the UV intensity at thousands of points and provide an approximation of the nominal average UV intensity within a particular reactor geometry and lamp configuration. This calculated intensity value can then be corrected for lamp age based on an empirical relation of decrease in UV intensity with lamp life available from the UV lamp manufacturer. A factor that still needs consideration is the decline in UV intensity due to fouling of the quartz sleeve surrounding each lamp. The impact of this factor can only be estimated empirically on a site specific basis. This was done at the EVMWD Regional plant by comparing the UV intensity derived from the mathematical SPSS model to the UV intensity derived from seeded MS2 bacteriophage inactivation data as detailed in Section 5. Differences between the two dose estimation methods as a function of lamp cleaning intervals was attributed to lamp fouling. This empirically derived fouling rate can then be used correct the SPSS model calculated UV intensity. The Regional Plant can then use this curve to determine a lamp cleaning interval which will insure maintenance of a specified minimum UV intensity at a defined operating lamp output.

MAINTAINING UV EXPOSURE TIME

A tracer study was performed on the EVMWD Regional Plant UV reactor on December 13, 1993. The test was run to determine the validity of using theoretical hydraulic detention times in calculating the UV exposure time. In order to use theoretical detention times it was necessary to establish that the hydrodynamic conditions for the UV contact chamber were plug-flow with minimal axial dispersion. This test was conducted to confirm the exposure times in the UV chamber, as well as to verify that the flow through the channel was plug-flow.

The tracer compound used for this test was a 5M sodium chloride solution. The change in conductance due to the tracer addition was monitored using a conductivity probe. The concentrated salt solution was fed into the channel with a progressive cavity pump through a PVC piping assembly placed in the UV contactor chamber one foot ahead of the first lamp bank. The piping assembly consisted of a 3/4 inch PVC rectangular grid with 8 holes distributed uniformly throughout the piping grid as shown in Figure 3-6.

The purpose of this apparatus was to distribute the tracer compound uniformly across the channel.

A preliminary test was conducted to determine the uniformity of the tracer throughout the crossection of the channel and to verify the stability of the response of the conductivity probe. The conductivity probe was placed in front of the first bank of UV lamps, one foot downstream of the point of tracer addition. While the tracer was being added to the wastewater stream , the conductivity probe was submerged near the surface of the water in the middle of the channel. Conductance readings were taken every 2 seconds for 16 seconds. Next the probe was lowered to the middle depth of the channel and again the conductance readings were recorded every 2 seconds for 16 seconds. The conductivity probe was then submerged near the surface of the water next to each wall of the channel. Readings were taken every 2 seconds for 16 seconds. The probe was then lowered to the middle depth of the channel next to the walls and again the conductance readings were recorded every 2 seconds for 16 seconds. The probe was then moved to one foot downstream of the end of the fifth bank and the test was repeated. The results of these tests are summarized in Tables 8-1 through 8-2. Figure 8-2 shows the points where the conductance measurements were taken. The conductance readings taken from the point just following the piping assembly are somewhat erratic since the probe is close to the point of initial mixing. The conductance readings at the end of the fifth bank are stable. The data show that the tracer is uniformly distributed at the end of the fifth bank of UV lamps.

For the tracer test the conductivity probe was placed one foot downstream of the fifth bank of UV lamps in the middle of the depth . The probe was approximately 46 ft. from the point of tracer addition as shown in Figure 8-2. A step dose of concentrated sodium chloride solution was injected into the wastewater flow which was measured at 86% of peak flow (2389 gpm). The conductivity was recorded every 2 seconds until an elevated level of conductance was achieved. A significant change in conductance was not observed until 46 seconds after the start of the tracer addition. After a steady-state elevated conductivity was established at the point of measurement, the tracer feed was discontinued and the decrease in conductivity was measured every two seconds until the conductivity returned to ambient levels. The results of this test are summarized in Appendix B.

TABLE 8-1

CONDUCTIVITY AT THE FIRST BANK OF UV LAMPS

Water Surface

Time Seconds	Wall A (umho/cm)	Center of Channel (umho/cm)	Wall B (umho/cm)
2	1970	2320	1520
4	2110	1950	2510
6	2180	2200	2590
8	2230	1800	2930
10	2350	1630	3310
12	2450	1550	3130
14	2610	1490	2980
16	2350	1590	2890

Middle Depth of Water

Time Seconds	Wall A (umho/cm)	Center of Channel (umho/cm)	Wall B (umho/cm)
2	1710	1780	1630
4	1750	1710	1720
6	2010	1630	1750
8	1730	1640	1660
10	1630	1560	1660
12	1950	1530	1630
14	2020	1510	1550
16	2100	1520	1510

TABLE 8-2

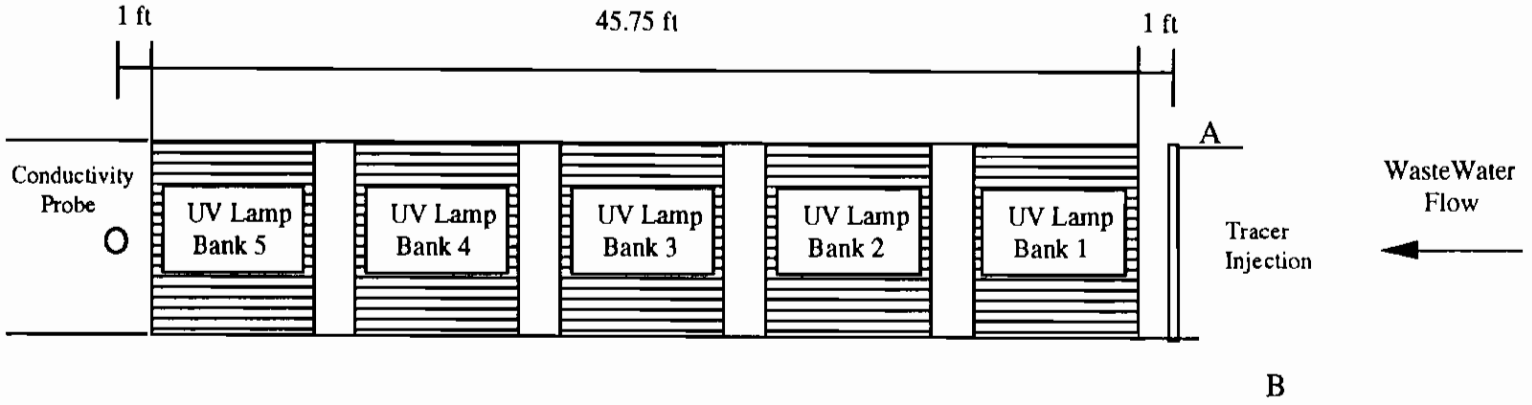
CONDUCTIVITY AT THE FIFTH BANK OF UV LAMPS

Water Surface

Time Seconds	Wall A (umho/cm)	Center of Channel (umho/cm)	Wall B (umho/cm)
2	1720	1770	1720
4	1720	1790	1720
6	1720	1790	1720
8	1720	1790	1740
10	1730	1780	1760
12	1740	1770	1750
14	1750	1760	1730
16	1770	1750	1730

Middle Depth of Water

Time Seconds	Wall A (umho/cm)	Center of Channel (umho/cm)	Wall B (umho/cm)
2	1900	1880	1840
4	1910	1860	1850
6	1920	1850	1870
8	1930	1850	1880
10	1940	1860	1890
12	1950	1870	1900
14	1960	1880	1900
16	1970	1890	1890



Water Flowrate = 2389 gpm
Water Depth = 2 ft
Channel Width = 3.75 ft
Theoretical Detetion Time = 67 sec.

SCHEMATIC OF THE UV CONTACT CHAMBER

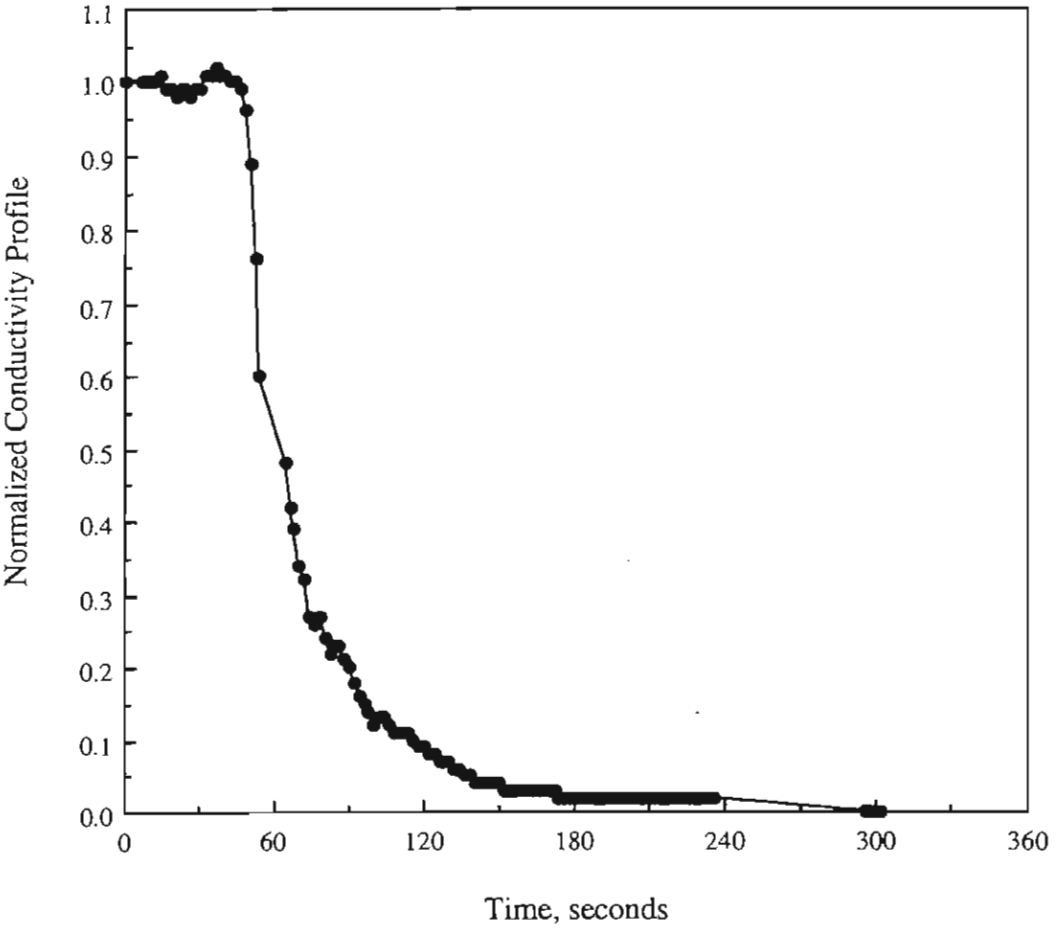
FIGURE 8-2

The curve plotted through the data in Figure 8-3 represents the change in conductivity as a function of time. In order to evaluate the rate of change of conductivity with time, which is analogous to the rate at which the tracer passes through the reactor, the slope of the curve presented in Figure 8-3 was determined as a function of time by taking the first derivative at each point in the curve. This resulted in a second curve, Figure 8-4, which is referred to as the residence time distribution (RTD) curve. Several numerical methods can be applied to the RTD curve to describe the hydrodynamic conditions of a particular system. The mean hydraulic detention time, tm, is defined as the centroid of the RTD curve. In this case, the mean hydraulic detention time was calculated at 70 seconds. Based on the channel dimensions, the water depth, and the wastewater flowrate, the theoretical detention time is estimated at 67 seconds. Figure 8-5 shows the percent of tracer that has passed the point of measurement as a function of time.

In order to determine the degree of axial mixing the tracer data were evaluated according to the dispersion model described by Levenspiel (1962). As the degree of axial mixing decreases, the mean detention time becomes a more accurate estimate of the actual hydraulic detention time. For UV disinfection, it has been recommended that the reactor design attempt to provide a dispersion number of less then 0.05 (U.S. EPA, 1986). The dispersion number was calculated to be 0.056. This dispersion number is sufficiently low to allow the use of theoretical detention times to approximate the actual detention times.

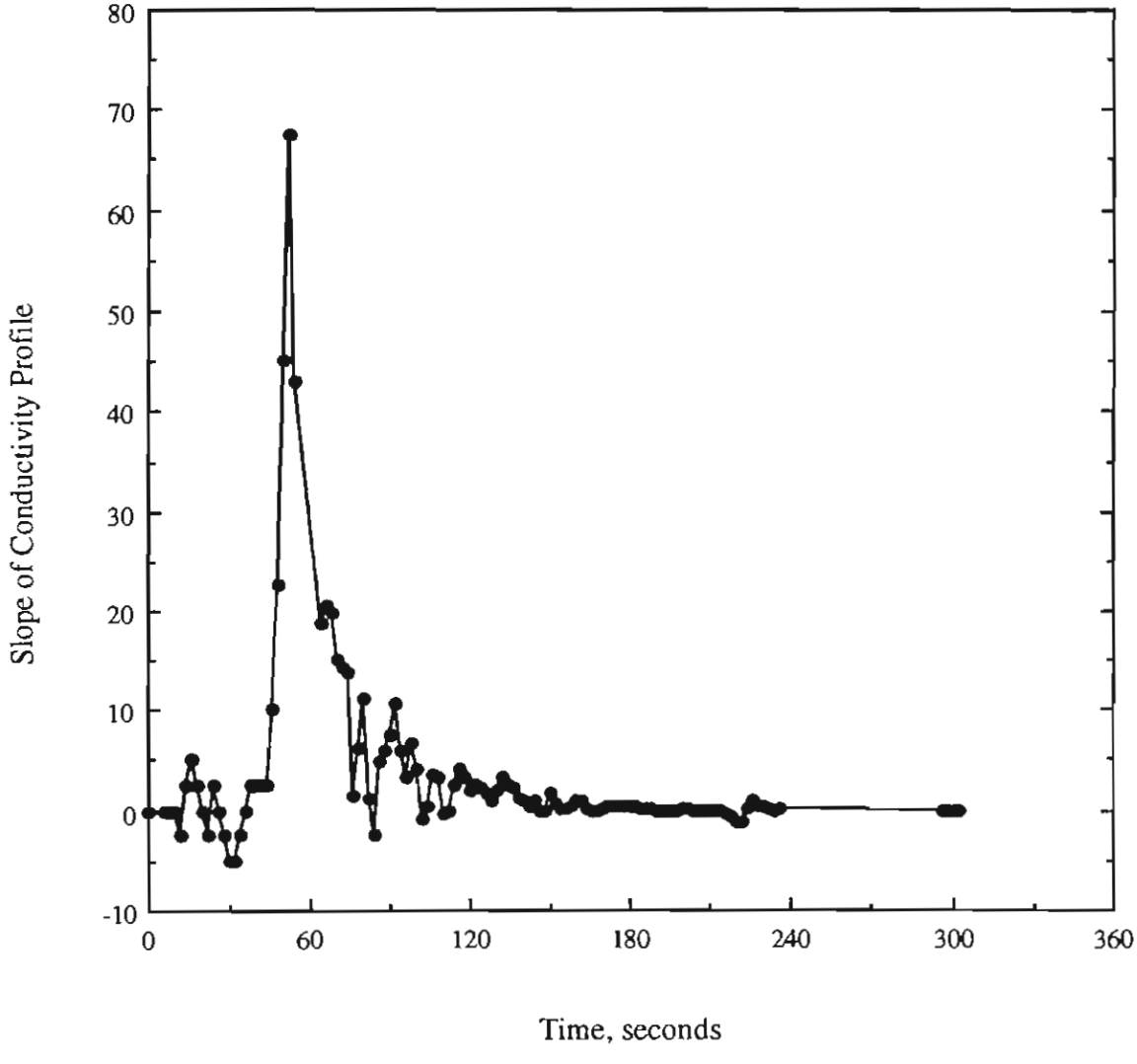
MAINTAINING AN EFFECTIVE UV DOSE

Utilizing the fouling curve developed in Section 5 and the results of the full-scale tracer study which demonstrate the adequacy of the theoretical detention time as an estimate of the actual detention time, a table can be developed indicating the minimum lamp cleaning frequency needed to maintain a minimum UV dose at different peak flow rates. This information, presented in Table 8-3, indicates that for the plant to maintain the 140 mW•sec/sq cm dose specified in the UV Disinfection Guidelines for Wastewater Reclamation in California at a peak flow of 2 mgd would require cleaning the UV lamps every 83 days at 70 % lamp output and every 115 days at 100 % lamp output. For a peak flow of 4 mgd, cleaning would be required every 40 days for 100% lamp output and the 140 mW•sec/sq cm dose would not be achievable at 70% lamp output.



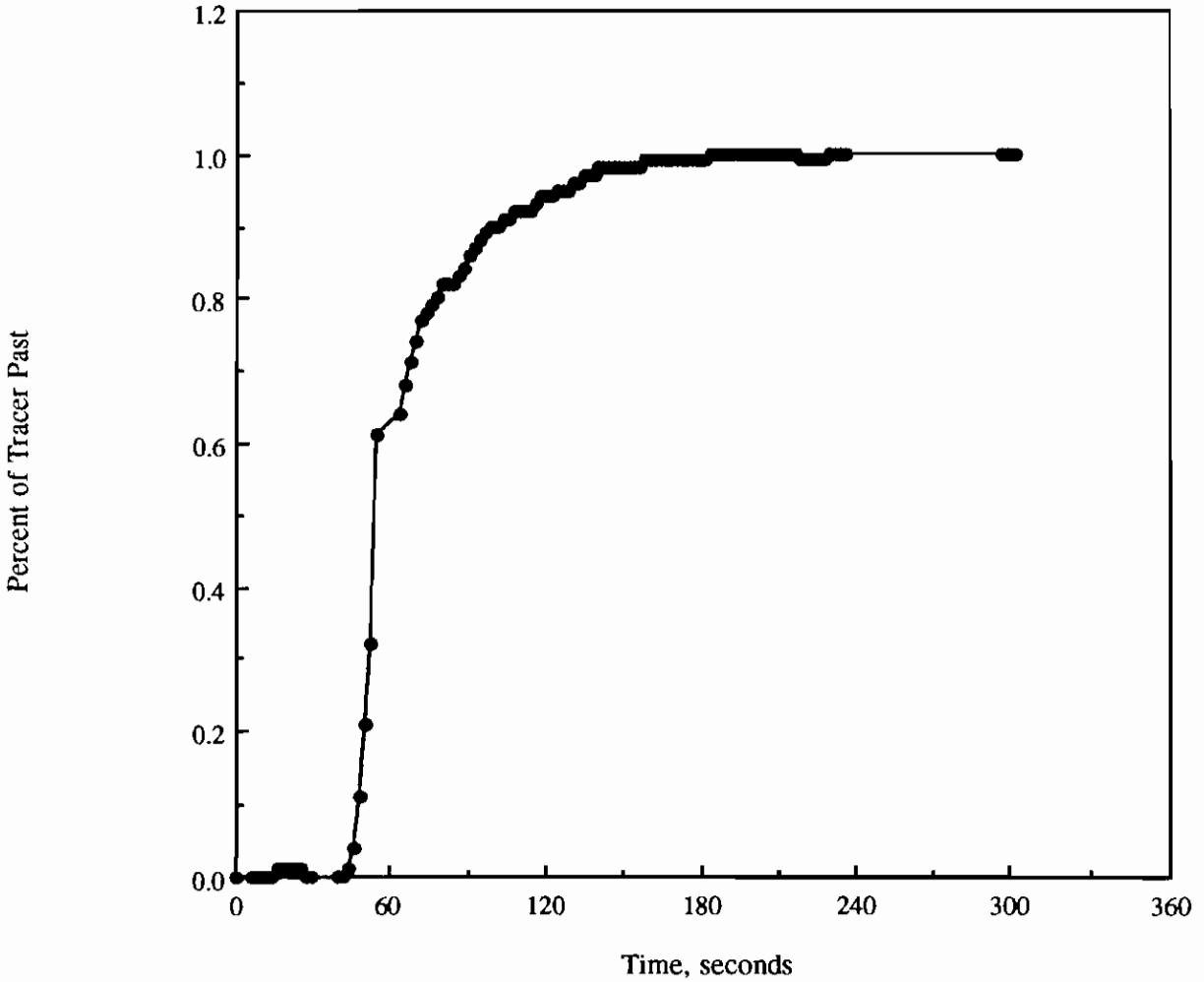
TRACER RESPONSE FOR THE EVMWD FULL-SCALE UV REACTOR

FIGURE 8-3



RESIDENCE TIME DISTRIBUTION FOR THE EVMWD FULL-SCALE UV REACTOR

FIGURE 8-4



PERCENT OF TRACER PAST MEASURING POINT

FIGURE 8-5

TABLE 8-3

MINIMUM LAMP CLEANING FREQUENCY REQUIRED TO MAINTAIN THE UV DISINFECTION GUIDELINES DOSE FOR WASTEWATER RECLAMATION AT DIFFERENT LAMP OUTPUTS AND FLOW RATES

Operating Condition	Q (mgd)	Cleaning Frequency (days)
Condition I (worst-case) -Transmittance 70% -UV Lamp output 70% -4 Banks on service	2 4	99 **
Condition II -Transmittance 70% -UV Lamp output 100% -4 Banks on service	2 4	140 46

** UV dose cannot be achieved

Calculation is based of the UV Disinfection Guidelines for Wastewater Reclamation in Calirornia Specified Dose of 140 mW•sec/sq cm.

Section 9

SECTION 9

CONCLUSIONS

UV light disinfection was shown to continuously provide total coliform, fecal coliform, *enterococci, fecal streptococci*, heterotrophic plate count, and polio virus inactivation equivalent to chorine at a full-scale tertiary treatment facility while reducing the formation of known carcinogenic disinfection by-products and the formation of chronic whole effluent toxicity.

The ability of UV light disinfection to provide microbial inactivation equivalent to chlorine was demonstrated at full-scale for a nitrified and partially denitrified filtered secondary effluent treated to meet the most stringent criterion of the California Wastewater Reclamation Criteria (total coliform ≤ 2.2 MPN/100 mL). The UV doses to achieve 4-log inactivation of indigenous bacteria and seeded virus were 75 mW•sec/sq cm for total coliform, 61 mW•sec/sq cm for fecal coliform, 91 mW•sec/sq cm for HPC, and 68 mW•sec/sq cm for poliovirus. Doses of 57 mW•sec/sq cm and 59 mW•sec/sq cm were needed to achieve 3-log inactivation of *fecal streptococci and enterococci.* A UV dose greater than 80 mW•sec/sq cm but less than 120 mW•sec/sq cm was demonstrated for compliance with the most stringent coliform criterion. A step-dose tracer study of the full-scale UV system was performed and demonstrated that the theoretical detention times could be used to approximate the actual detention time in calculation of the full-scale UV dose. The chlorine Ct values demonstrated to inactive the target organisms below detection limit for the full-scale contactor were ≤ 43 mg/L•sec for total coliform, ≤ 30 mg/L•sec for fecal coliform, ≤ 5 mg/L•sec for fecal streptococci, ≤5 mg/L•sec for enterococci, >160 mg/L•sec for HPC, and 63 mg/L•sec for polio virus. Therefore, application of a UV dose of 120 mW•sec/sq cm or 10 mg/L of chlorine applied for a 2-hour contact time should inactivate fecal coliform, *fecal streptococci, enterococci,* and viruses below detection limits. For both disinfectants, as much as one or two logs of HPC can still be present after disinfection at these doses.

Inactivation experiments were also performed at bench-scale utilizing the full-scale filtered secondary effluent. Accurate estimates of full-scale UV inactivation performance were obtained from these bench-scale studies. All of the the full-scale inactivation doses fell within the confidence intervals calculated for the bench-scale inactivation doses with the exception of fecal coliform where the bench-scale dose under predicted the full-scale dose

by 77%. Because good agreement between bench-scale and full-scale inactivation doses was observed for total coliform, this finding was not investigated further.

Full-scale UV inactivation was measured at various stages of lamp fouling. The effect of fouling on the calculated UV dose was determined by comparing the single point source summation (SPSS) model calculated UV doses with the SPSS doses adjusted by MS2 bioassay calibration data. This was achieved by seeding the full-scale facility with MS2 bacteriophage and comparing the full-scale inactivation to a collimated beam MS2 inactivation calibration curve. This resulted in the generation of a fouling curve which demonstrated that the percentage of fouling appeared to be a linear function of the number of elapsed days since lamp cleaning. To test the validity of the fouling curve, a discrete set of full-scale inactivation data were collected, the SPSS calculated UV doses were adjusted based on the fouling curve, and the 4-log inactivation dose calculated for each target organism was compared with the 4-log inactivation doses obtained from an different data set where the SPSS calculated UV dose had been adjusted based on MS2 calibration data. No significant differences were observed between the two sets of UV inactivation doses, indicating the potential usefulness of this type of fouling curve in enabling a treatment facility employing UV disinfection to calculate the appropriate lamp cleaning frequency required to maintain a specified minimum UV dose.

Transformations of organic matter as a result of chlorine and UV disinfection were investigated at bench-scale utilizing high performance liquid chromatography coupled with UV detection or gas chromatography coupled with mass spectrometry. A chlorine dose of 10 mg/L and contact time of 120 minutes was used to mimic full-scale plant disinfection. A very high UV dose of approximately 2800 mW•sec/sq cm was used to enhance production of UV by-products. This is a much higher dose than the 80 to 120 mW•sec/sq cm dose range demonstrated to inactivate the target organisms. The only disinfection by-products detected without sample preconcentration techniques were the trihalomethanes and these were only formed during the chlorination process. All other by-products were only detected in preconcentrated samples. A closed-loop stripping preconcentration technique was used prior to GC/MS analysis of volatile and semi-volatile compounds. Lyophilization or HPLC precolumn concentration was used prior to HPLC/UV analysis of the more polar, less volatile compounds.

The high concentrations of THMs (approximately 75 ug/L) measured in the chlorinated effluent were expected due to the predominance of free chlorine in the nitrified and partially denitrified effluent. No measurable THMs were produced in the UV irradiated effluent. A unique mid-polarity UV by-product peak was identifed by HPLC/UV analysis of the lyophilized UV irradiated sample. This peak was identified in two separate bench-scale experiments performed several months apart. The peak was not found in a UV irradiated sample collected from the full-scale plant. Failure to produce this UV by-product peak at full-scale was probably due either to the much lower UV dose of 188 mW•sec/sq cm applied at full-scale or the additional full-scale dilution of this compound to a concentration level below the analytical detection limit. Attempts to identify this UV peak with low and high resolution fast atom bombardment (FAB)/MS were not successful. A unique chlorinated by-product peak was identifed by HPLC/UV analysis of the lyophilized chlorinated sample. The peak was identified as two separate compounds with molecular weights of approximately 461.1 and 461.3 daltons. Further structural identification of the compounds was not performed.

The apparent lack of significant UV byproducts is not unexpected due to the much lower molar absorption extinction coefficient of organic carbon bonds as compared with the extinction coefficients for nitrogenous heterocyclic bases of the DNA/RNA nucleotides where UV inactivation occurs through pyrimidine dimerization.

Bioassay testing of the full-scale plant filtered secondary effluent, chlorinated filtered secondary effluent, and UV irradiated filtered secondary effluent indicated production of chronic toxicity from the chlorination process. This chronic toxicity was measured as a decline in the reproductive rate of Ceriodaphnia dubia. No chronic toxicity was evident from the UV irradiation process.

Appendix A

MONTGOMERY WATSON

Cl Sample	Chlorine	Chlorine	Chlorine	Time	Adj. CT,	Total Coliform	Fecal Coliform	Fecal Streptococci	Enterococci	HPC	MS2	Polio
Data from Run 1 - 2/10/93 (JML/EBB)												
					2.19 mgd	Avg Flowrate, Split50%						
raw	0.10	0.15	0.05	2	0.20	5.00E+04	5.00E+04	5.00E+03	5.00E+03	6.30E+04	-	-
CL-IN	2.50	2.60	0.10		0.00							
A	1.40	1.55	0.15	37	52.08	2.30E+01 <	2.00E+00 <	2.00E+00 <	2.00E+00	6.50E+01	-	-
B	0.85	0.95	0.10	45	58.84	8.00E+00	8.00E+00 <	2.00E+00 <	2.00E+00	1.20E+02	-	-
C	0.80	0.95	0.15	88	92.01	2.00E+00	4.00E+00 <	2.00E+00 <	2.00E+00	7.80E+01	-	-
D	0.30	0.50	0.20	161	114.50	4.00E+00	2.00E+00 <	2.00E+00 <	2.00E+00	2.00E+01	-	-
E	0.20	0.35	0.15	207	123.69	1.30E+01	1.30E+01 <	2.00E+00 <	2.00E+00	8.20E+01	-	-
Log N/No												
raw	0.10	0.15	0.05	2	0.20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	1.40	1.55	0.15	37	52.08	-3.34E+00 >	-4.40E+00 >	-3.40E+00 >	-3.40E+00	-2.99E+00		
B	0.85	0.95	0.10	45	58.84	-3.80E+00	-3.80E+00 >	-3.40E+00 >	-3.40E+00	-2.72E+00		
C	0.80	0.95	0.15	88	92.01	-4.40E+00	-4.10E+00 >	-3.40E+00 >	-3.40E+00	-2.91E+00		
D	0.30	0.50	0.20	161	114.50	-4.10E+00	-4.40E+00 >	-3.40E+00 >	-3.40E+00	-3.50E+00		
E	0.20	0.35	0.15	207	123.69	-3.59E+00	-3.59E+00 >	-3.40E+00 >	-3.40E+00	-2.89E+00		
Data from Run 2 - 2/25/93 (EBB)												
					2.50 mgd	Avg Flowrate, Split50%						
raw <	0.05 <	0.05	0.00	0	0.00	1.40E+05	3.00E+04	9.00E+03	5.00E+03	5.70E+04	-	-
CL-IN <	0.05 <	0.05			0.00							
A*	0.45	0.60	0.15	32	14.59	7.00E+00	4.00E+00 <	2.00E+00 <	2.00E+00	1.10E+02	-	-
B	1.10	1.25	0.15	76	62.18	4.00E+00	2.00E+00 <	2.00E+00 <	2.00E+00	3.90E+01	-	-
C	0.50	0.65	0.15	112	80.32 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	2.20E+01	-	-
D	0.30	0.45	0.15	141	89.11 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	2.90E+01	-	-
E	0.25	0.40	0.15	181	99.15 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	9.50E+01	-	-
Log N/No												
raw	0.05 >	0.05	0.00	0	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A*	0.45	0.60	0.15	32	14.59	-4.30E+00	-3.88E+00 >	-3.65E+00 >	-3.40E+00	-2.71E+00		
B	1.10	1.25	0.15	76	62.18	-4.54E+00	-4.18E+00 >	-3.65E+00 >	-3.40E+00	-3.16E+00		
C	0.50	0.65	0.15	112	80.32 >	-4.85E+00 >	-4.18E+00 >	-3.65E+00 >	-3.40E+00	-3.41E+00		
D	0.30	0.45	0.15	141	89.11 >	-4.85E+00 >	-4.18E+00 >	-3.65E+00 >	-3.40E+00	-3.29E+00		
E	0.25	0.40	0.15	181	99.15 >	-4.85E+00 >	-4.18E+00 >	-3.65E+00 >	-3.40E+00	-2.78E+00		
* chlorine shutdown during sampling at A												
Data from Run 3 - 3/11/93 (EBB)												
					2.38 mgd	Avg Flowrate, Split50%						
raw	0.00	0.00		0	0.00	8.00E+04	1.70E+04	8.00E+02	3.30E+01	NA	-	-
CL-IN >	3.50 >	3.50			0.00							
4	2.50	2.75	0.25	34	85.30	8.00E+00	2.00E+00 <	2.00E+00 <	2.00E+00	NA	-	-
B	0.75	0.90	0.15	80	119.45 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	NA	-	-
C	0.55	0.70	0.15	118	140.46 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	NA	-	-
D	0.35	0.50	0.15	149	151.26	8.00E+01 <	2.00E+00 <	2.00E+00 <	2.00E+00	NA	-	-
E	0.30	0.45	0.15	191	163.94	2.20E+02 <	2.00E+00 <	2.00E+00 <	2.00E+00	NA	-	-
Log N/No												
raw	0.00	0.00	0.00	0	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00			
4	2.50	2.75	0.25	34	85.30	-4.00E+00	-3.93E+00 >	-2.60E+00 >	-1.22E+00			
B	0.75	0.90	0.15	80	119.45 >	-4.60E+00 >	-3.93E+00 >	-2.60E+00 >	-1.22E+00			
C	0.55	0.70	0.15	116	140.46 >	-4.60E+00 >	-3.93E+00 >	-2.60E+00 >	-1.22E+00			
D	0.35	0.50	0.15	149	151.26	-3.00E+00 >	-3.93E+00 >	-2.60E+00 >	-1.22E+00			
E	0.30	0.45	0.15	181	163.94	-2.56E+00 >	-3.93E+00 >	-2.60E+00 >	-1.22E+00			
										Background contamination		
Data from Run 4 - 3/24/93 (EBB)												
					2.13 mgd	Avg Flowrate, Split50%						
raw	0.00	0.00	0.00	0	0.00	1.30E+05	2.30E+04	1.70E+03	1.30E+03	4.30E+04	-	-
CL-IN >	3.50 >	3.50			0.00							
A	3.50 >	3.50 >	0.00	38	133.46	4.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	1.50E+01	-	-
B	1.20	1.35	0.15	89	194.54	4.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	1.00E+00	-	-
C	0.30	0.45	0.15	132	207.35	8.00E+00	2.00E+00 <	2.00E+00 <	2.00E+00	2.00E+01	-	-
D	0.60	0.80	0.20	166	226.04 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	2.10E+01	-	-
E	1.00	1.40	0.40	213	275.29	2.00E+00	2.00E+00 <	2.00E+00 <	2.00E+00	9.00E+00	-	-
Log N/No												
raw	0.00	0.00	0.00	0	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	3.50 >	3.50 >	0.00	38	133.46	-4.51E+00 >	-4.08E+00 >	-2.93E+00 >	-2.81E+00	-3.46E+00		
B	1.20	1.35	0.15	89	194.54	-4.51E+00 >	-4.08E+00 >	-2.93E+00 >	-2.81E+00 >	-4.63E+00		
C	0.30	0.45	0.15	132	207.35	-4.21E+00	-4.08E+00 >	-2.93E+00 >	-2.81E+00	-3.33E+00		
D	0.60	0.80	0.20	166	226.04 >	-4.81E+00 >	-4.08E+00 >	-2.93E+00 >	-2.81E+00	-3.31E+00		
E	1.00	1.40	0.40	213	275.29	-4.81E+00	-4.08E+00 >	-2.93E+00 >	-2.81E+00	-3.68E+00		

Cl Sample		Chlorine		Chlorine		Chlorine	Time	Adj. CT,		Total Coliform		Fecal Coliform		Fecal Streptococci		Enterococci		HPC	MS2	Polio
Data from Run 5 - 4/28/93 (EBB)																				
								1.66 mgd		Avg Flowrate, Split50%										
raw		0.00		0.00		0.00	0	0.00		1.30E+05		8.00E+04		5.00E+03		1.70E+03		5.90E+04	-	-
CL-IN	>	3.60	>	3.50				0.00												
A	>	3.60	>	3.50	>	0.00	46	168.08	<	2.00E+00	<	2.00E+00		2.00E+00	<	2.00E+00		5.00E+00	-	-
B		2.30		2.60		0.50	112	315.48	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+00	-	-
C		2.00		2.50		0.50	186	423.00		2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+00	-	-
D		1.60		2.30		0.50	209	501.17	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		1.60E+01	-	-
E		0.80		1.30		0.50	269	548.77	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+00	-	-
Log N/No																				
raw		0.00		0.00		0.00	0	0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A	>	3.50	>	3.60	>	0.00	46	168.08	>	-4.61E+00	>	-4.60E+00		-3.40E+00	>	-2.93E+00		-4.07E+00		
B		2.30		2.60		0.50	112	315.48	>	-4.61E+00	>	-4.60E+00	>	-3.40E+00	>	-2.93E+00	>	-4.77E+00		
C		2.00		2.50		0.50	186	423.00		-4.61E+00	>	-4.60E+00	>	-3.40E+00	>	-2.93E+00	>	-4.77E+00		
D		1.60		2.30		0.50	209	501.17	>	-4.61E+00	>	-4.60E+00	>	-3.40E+00	>	-2.93E+00		-3.57E+00		
E		0.80		1.30		0.50	269	548.77	>	-4.61E+00	>	-4.60E+00	>	-3.40E+00	>	-2.93E+00	>	-4.77E+00		
Data from Run 6 - 5/13/93 (EBB)																				
								2.00 mgd		Avg Flowrate, Split50%										
raw		0.00		0.00	>	0.00	0	0.00		1.70E+05		3.00E+04		5.00E+03		5.00E+03		8.20E+04	-	-
CL-IN	>	3.50	>	3.50				0.00												
A	>	3.00		3.25		0.25	41	121.55		2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		1.00E+01	-	-
B		1.20		1.50		0.30	95	166.44	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+00	-	-
C		1.00		1.30		0.30	140	231.80	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		4.50E+00	-	-
D		0.60		1.20		0.40	177	261.11	<	2.00E+00		2.00E+00	<	2.00E+00	<	2.00E+00		2.50E+00	-	-
E		0.40		0.70		0.30	227	281.19	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		3.10E+01	-	-
Log N/No																				
raw		0.00		0.00	>	0.00	0	0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A	>	3.00		3.25		0.25	41	121.55		-4.83E+00	>	-4.18E+00	>	-3.40E+00	>	-3.40E+00	>	-3.91E+00		
B		1.20		1.50		0.30	95	166.44	>	-4.83E+00	>	-4.18E+00	>	-3.40E+00	>	-3.40E+00	>	-4.91E+00		
C		1.00		1.30		0.30	140	231.80	>	-4.83E+00	>	-4.18E+00	>	-3.40E+00	>	-3.40E+00		-4.26E+00		
D		0.60		1.20		0.40	177	261.11	>	-4.83E+00		-4.18E+00	>	-3.40E+00	>	-3.40E+00		-4.52E+00		
E		0.40		0.70		0.30	227	281.19	>	-4.83E+00	>	-4.18E+00	>	-3.40E+00	>	-3.40E+00		-3.42E+00		
Data from Run 7 - 5/19/93 (EBB)																				
								1.95 mgd		Avg Flowrate,split 50%										
raw		0.00		0.00		0.00	0	0.00		5.00E+04		2.20E+04		1.30E+03		9.00E+01		5.10E+04	-	-
CL-IN		3.50						0.00												
A		1.80		2.10		0.30	42	74.80		2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		1.20E+02	-	-
B		1.30		1.60		0.30	97	146.90	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		3.50E+00	-	-
C		1.00		1.30		0.30	144	193.43		5.00E+02		7.00E+01		9.00E+01	<	2.00E+00		1.20E+02	-	-
D		0.60		0.90		0.30	161	215.97	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		3.50E+00	-	-
E		0.40		0.60		0.20	233	236.57	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		5.40E+01	-	-
Log N/No																				
raw		0.00		0.00		0.00	0	0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A		1.80		2.10		0.30	42	74.80		-4.40E+00	>	-4.04E+00	>	-2.81E+00	>	-1.65E+00		-2.63E+00		
B		1.30		1.60		0.30	97	146.90	>	-4.40E+00	>	-4.04E+00	>	-2.81E+00	>	-1.65E+00		-4.16E+00		
C		1.00		1.30		0.30	144	193.43		-2.00E+00		-2.50E+00		-1.16E+00	>	-1.65E+00		-2.63E+00		
D		0.60		0.90		0.30	161	215.97	>	-4.40E+00	>	-4.04E+00	>	-2.81E+00	>	-1.65E+00		-4.16E+00		
E		0.40		0.60		0.20	233	236.57	>	-4.40E+00	>	-4.04E+00	>	-2.81E+00	>	-1.65E+00		-2.98E+00		

Cl Sample	Chlorine	Chlorine	Chlorine	Time	Adj. CT,		Total Coliform		Fecal Coliform		Fecal Streptococci		Enterococci		HPC	MS2	Polio
Data from Run 8 - 5/26/93 (EBB)																	
					2.00 mgd		Avg Flowrate,split 50%										
raw	0.00	0.00	0.00	0	0.00		1.30E+05		2.20E+04		2.40E+03		2.40E+03		8.90E+04	-	-
CL-IN	3.20	3.40			0.00												
A	2.70	3.00	0.30	41	109.39	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+01	-	-
B	1.20	1.50	0.30	95	174.29	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		3.00E+00	-	-
C	0.80	1.00	0.20	140	210.57	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+00	-	-
D	0.30	0.50	0.20	177	221.57	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		5.50E+00	-	-
E	0.10	0.35	0.25	227	228.59		2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		1.40E+02	-	-
Log N/No																	
raw	0.00	0.00	0.00	0	0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A	2.70	3.00	0.30	41	109.39	>	-4.81E+00	>	-4.04E+00	>	-3.08E+00	>	-3.08E+00	>	-3.95E+00		
B	1.20	1.50	0.30	95	174.29	>	-4.81E+00	>	-4.04E+00	>	-3.08E+00	>	-3.08E+00		-4.47E+00		
C	0.80	1.00	0.20	140	210.57	>	-4.81E+00	>	-4.04E+00	>	-3.08E+00	>	-3.08E+00	>	-4.95E+00		
D	0.30	0.50	0.20	177	221.57	>	-4.81E+00	>	-4.04E+00	>	-3.08E+00	>	-3.08E+00		-4.21E+00		
E	0.10	0.35	0.25	227	228.59		-4.81E+00	>	-4.04E+00	>	-3.08E+00	>	-3.08E+00		-2.80E+00		
Data from Run 9 -6/2/93 (JML/EBB)																	
					1.85 mgd		Avg Flowrate,split 50%										
raw	0.00	0.00	0.00	0	0.00		1.30E+05		8.00E+04		3.00E+03		2.30E+03		2.20E+05	-	-
CL-IN	3.85	4.00			0.00												
A	1.20	1.40	0.20	44	52.58	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		1.50E+02	-	-
B	0.40	0.55	0.15	102	75.95	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		3.00E+00	-	-
C	0.25	0.40	0.15	151	88.21	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		3.40E+01	-	-
D	0.15	0.30	0.15	191	94.15	<	2.00E+00	<	2.00E+00		1.10E+02	<	2.00E+00		5.30E+02	-	-
E	0.10	0.25	0.15	245	99.57		1.70E+01	<	2.00E+00		2.00E+00	<	2.00E+00		1.10E+03	-	-
Log N/No																	
raw	0.00	0.00	0.00	0	0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A	1.20	1.40	0.20	44	52.58	>	-4.81E+00	>	-4.80E+00	>	-3.18E+00	>	-3.08E+00		-3.17E+00		
B	0.40	0.55	0.15	102	75.95	>	-4.81E+00	>	-4.80E+00	>	-3.18E+00	>	-3.08E+00		-4.87E+00		
C	0.25	0.40	0.15	151	88.21	>	-4.81E+00	>	-4.80E+00	>	-3.18E+00	>	-3.08E+00		-3.81E+00		
D	0.15	0.30	0.15	191	94.15	>	-4.81E+00	>	-4.80E+00		-1.44E+00	>	-3.08E+00		-2.82E+00		
E	0.10	0.25	0.15	245	99.57		-3.68E+00	>	-4.80E+00		-3.18E+00	>	-3.08E+00		-2.30E+00		
Data from Run 10 -6/9/93 (JML/EBB)																	
					1.81 mgd		Avg Flowrate,Split50%										
raw	0.00	0.00	0.00	0	0.00		7.00E+04		3.00E+04		8.00E+02		8.00E+02		5.10E+04	-	-
CL-IN	3.50	3.80		0	0.00												
A	1.80	2.10	0.30	45	80.47		8.00E+00		2.00E+00	<	2.00E+00	<	2.00E+00		1.00E+01	-	-
B	1.10	1.40	0.30	104	148.11	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		7.50E+00	-	-
C	0.90	1.20	0.30	154	191.18	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		2.00E+00	-	-
D	0.35	0.85	0.30	195	205.31	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		8.00E+00	-	-
E	0.25	0.50	0.25	250	219.18		2.00E+00		2.00E+00	<	2.00E+00	<	2.00E+00		6.00E+00	-	-
Log N/No																	
raw	0.00	0.00	0.00	0	0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A	1.80	2.10	0.30	45	80.47		-3.94E+00		-4.18E+00	>	-2.60E+00	>	-2.60E+00		-3.71E+00		
B	1.10	1.40	0.30	104	148.11	>	-4.54E+00	>	-4.18E+00	>	-2.60E+00	>	-2.60E+00		-3.63E+00		
C	0.90	1.20	0.30	154	191.18	>	-4.54E+00	>	-4.18E+00	>	-2.60E+00	>	-2.60E+00		-4.41E+00		
D	0.35	0.85	0.30	195	205.31	>	-4.54E+00	>	-4.18E+00	>	-2.60E+00	>	-2.60E+00		-3.93E+00		
E	0.25	0.50	0.25	250	219.18		-4.54E+00		-4.18E+00	>	-2.60E+00	>	-2.60E+00		-3.93E+00		

Cl Sample		Chlorine	Chlorine	Chlorine	Time	Adj. CT		Total Coliform		Fecal Coliform		Fecal Streptococci		Enterococci		HPC		MS2	Polio
Data from Run 11 -6/16/93 -MS2 SEEDING(JML/EBB)																			
						1.80 mgd		Avg Flowrate,Split50%											
raw		0.00	0.00	0.00	0	0.00		8.00E+04		5.00E+04		3.00E+03		1.70E+03		1.10E+05		5.00E+05	-
CL-IN		3.80	4.00			0.00													
A		0.85	1.10	0.25	45	38.26		2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		5.00E+00	<	1.00E+00	-
B		0.15	0.30	0.15	105	47.28		1.30E+01		8.00E+00		8.00E+00		4.00E+00		9.90E+02	<	1.00E+00	-
C	<	0.05	0.15	0.10	158	49.80		NA		NA		NA		NA		NA	<	1.00E+00	-
D	<	0.05	0.15	0.10	196	51.83		NA		NA		NA		NA		NA	<	1.00E+00	-
E		NA	0.10	NA	252			NA		NA		NA		NA		NA	<	1.00E+00	-
Log N/No																			
raw		0.00	0.00	0.00	0	0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00	
A		0.85	1.10	0.25	45	38.26		-4.60E+00	>	-4.40E+00	>	-3.18E+00	>	-2.93E+00		-4.34E+00		-5.70E+00	
B		0.15	0.30	0.15	105	47.28		-3.79E+00		-3.80E+00		-2.57E+00		-2.83E+00		-2.05E+00		-5.70E+00	
C		0.05	0.15	0.10	158	49.80												-5.70E+00	
D		0.05	0.15	0.10	196	51.83												-5.70E+00	
E		NA	0.10	NA	252	0.00												-5.70E+00	
NA=Not Analyzed/Not Available																			
Data from Run 12 -6/23/93 (JML/EBB)																			
						1.98 mgd		Avg Flowrate,Split50%											
raw		0.00	0.00	0.00	0	0.00		2.30E+04		2.30E+04		1.30E+03		8.00E+02		1.00E+05		-	-
CL-IN		3.80	4.00			0.00													
A		2.80	2.90	0.30	41	108.87		2.00E+00		2.00E+00	<	2.00E+00	<	2.00E+00		2.00E+01		-	-
B		1.00	1.30	0.30	98	181.44		2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		7.00E+00		-	-
C		0.70	1.00	0.30	142	193.59	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		8.50E+00		-	-
D		0.30	0.80	0.30	179	204.72	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		1.30E+01		-	-
E		0.20	0.50	0.30	230	214.89	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		3.10E+01		-	-
Log N/No																			
raw		0.00	0.00	0.00	0	0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00			
A		2.80	2.90	0.30	41	108.87		-4.08E+00		-4.08E+00	>	-2.81E+00	>	-2.80E+00		-3.70E+00			
B		1.00	1.30	0.30	98	181.44		-4.08E+00	>	-4.08E+00	>	-2.81E+00	>	-2.80E+00		-4.15E+00			
C		0.70	1.00	0.30	142	193.59	>	-4.08E+00	>	-4.08E+00	>	-2.81E+00	>	-2.80E+00		-4.19E+00			
D		0.30	0.80	0.30	179	204.72	>	-4.08E+00	>	-4.08E+00	>	-2.81E+00	>	-2.80E+00		-3.89E+00			
E		0.20	0.50	0.30	230	214.89	>	-4.08E+00	>	-4.08E+00	>	-2.81E+00	>	-2.80E+00		-3.51E+00			

Cl Sample	Chlorine	Chlorine	Chlorine	Time	Adj. CT,	Total Coliform	Fecal Coliform	Fecal Streptococci	Enterococci	HPC	MS2	Polio
Data from Run 13 -8/29/93 (JML/EBB)												
					1.65 mgd	Avg Flowrate,Split50%						
raw	0.00	0.00	0.00	0	0.00	7.00E+04	5.00E+04	2.40E+03	3.00E+03	3.70E+04	-	-
CL-IN	4.00	4.40			0.00							
A	2.20	2.50	0.30	44	98.38	2.00E+00	2.00E+00	< 2.00E+00	< 2.00E+00	5.00E+01	-	-
B	1.00	1.30	0.30	102	154.83	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	2.00E+00	-	-
C	0.70	1.00	0.30	151	189.15	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	1.00E+00	-	-
D	0.40	0.60	0.20	191	205.00	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 1.00E+00	-	-
E	0.25	0.50	0.25	245	218.56	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	3.30E+01	-	-
Log N/No												
raw	0.00	0.00	0.00	0	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	2.20	2.50	0.30	44	98.38	-4.54E+00	-4.40E+00	> -3.08E+00	> -3.18E+00	-2.87E+00		
B	1.00	1.30	0.30	102	154.83	> -4.54E+00	> -4.40E+00	> -3.08E+00	> -3.18E+00	-4.27E+00		
C	0.70	1.00	0.30	151	189.15	> -4.54E+00	> -4.40E+00	> -3.08E+00	> -3.18E+00	-4.57E+00		
D	0.40	0.80	0.20	191	205.00	> -4.54E+00	> -4.40E+00	> -3.08E+00	> -3.18E+00	> -4.57E+00		
E	0.25	0.50	0.25	245	218.56	> -4.54E+00	> -4.40E+00	> -3.08E+00	> -3.18E+00	-3.05E+00		
Date from Run 14 -7/7/93 (JML/EBB)												plu/100L
					1.63 mgd	Avg Flowrate,Split50%						
raw	0.00	0.00	0.00	0	0.00	4.80E+03	2.40E+04	1.10E+03	1.10E+03	6.10E+04	1.10E+04	
CL-IN	2.60	3.20			0.00							
A	1.50	1.80	0.30	50	74.80	2.00E+00	2.00E+00	< 2.00E+00	< 2.00E+00	< 1.00E+01	9.20E+03	
B	1.20	1.60	0.40	118	154.67	5.00E+01	< 2.00E+00	< 2.00E+00	< 2.00E+00	1.30E+02	3.40E+03	
C	0.70	1.10	0.40	172	193.75	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	2.00E+00	6.00E+02	
D	0.50	0.90	0.40	217	216.30	2.20E+01	2.20E+01	< 2.00E+00	< 2.00E+00	1.00E+00	6.30E+02	
E	0.25	0.60	0.35	279	231.74	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 1.00E+01	3.50E+01	
Raw/Polio	NA			0	0.00							2.64E+04
A'	4.80	4.80	0.20	5	22.14							5.40E+02
B'	4.40	4.60	0.20	10	43.31							< 1.00E+00
C'	4.00	4.30	0.30	14	62.57							8.00E+00
D'	3.80	3.80	0.20	19	79.89							< 1.00E+00
E'	3.00	3.40	0.40	24	94.33							< 1.00E+00
Log N/No												
raw	0.00	0.00	0.00	0	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
A	1.50	1.80	0.30	50	74.80	-3.38E+00	-4.08E+00	> -2.74E+00	> -2.74E+00	> -3.79E+00	-7.76E-02	
B	1.20	1.60	0.40	118	154.67	-1.98E+00	> -4.08E+00	> -2.74E+00	> -2.74E+00	-2.87E+00	-5.10E-01	
C	0.70	1.10	0.40	172	193.75	> -3.36E+00	> -4.08E+00	> -2.74E+00	> -2.74E+00	-4.48E+00	-1.26E+00	
D	0.50	0.90	0.40	217	216.30	-2.32E+00	-3.04E+00	> -2.74E+00	> -2.74E+00	-4.79E+00	-1.24E+00	
E	0.25	0.60	0.35	279	231.74	> -3.36E+00	> -4.08E+00	> -2.74E+00	> -2.74E+00	> -3.79E+00	-2.50E+00	
Raw/Polio	NA	0.00	0.00	0	0.00							0.00E+00
A'	4.80	4.80	0.20	5	22.14							
B'	4.40	4.80	0.20	10	43.31							-1.69E+00
C'	4.00	4.30	0.30	14	62.57							-4.42E+00
D'	3.60	3.80	0.20	19	79.89							-3.64E+00
E'	3.00	3.40	0.40	24	94.33							-4.42E+00

UV Bank	UV Int. Met. mW/cm2	UV Dose Mod mW•sec/cm2	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/100L
Data from Run 1 - 2/10/93 (JML/EBB)														
	1,318 hrs	2.19	Average flowrate,split50%											
raw	0.0	0.00					0.00	3.00E+05	1.10E+05	7.00E+03	2.60E+03	5.50E+04	-	-
A	2.8	71.54					68.00	2.40E+02 <	2.00E+00 <	2.00E+00 <	2.00E+00	2.00E+01	-	-
B	2.5	143.07	1/28/93	5	4.94	0.95	136.01	1.10E+01 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	1.00E+00	-	-
C	2.0	214.61					204.01	4.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	1.50E+01	-	-
D	1.9	286.14					272.01	2.00E+00 <	4.00E+00 <	2.00E+00 <	2.00E+00	2.50E+00	-	-
E	2.0	357.68					340.02 <	2.00E+00	2.00E+00 <	2.00E+00 <	2.00E+00 <	1.00E+00	-	-
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	2.8	71.54					68.00	-3.10E+00 >	-4.74E+00 >	-3.54E+00 >	-3.11E+00	-3.44E+00		
B	2.5	143.07					136.01	-4.44E+00 >	-4.74E+00 >	-3.54E+00 >	-3.11E+00 >	-4.74E+00		
C	2.0	214.61					204.01	-4.88E+00 >	-4.74E+00 >	-3.54E+00 >	-3.11E+00	-3.56E+00		
D	1.9	286.14					272.01	-5.16E+00	-4.44E+00 >	-3.54E+00 >	-3.11E+00	-4.34E+00		
E	2.0	357.68					340.02 >	-5.18E+00	-4.74E+00 >	-3.54E+00 >	-3.11E+00 >	-4.74E+00		
Data from Run 2 - 2/25/93 (EBB)														
	1,675 hrs	2.50	Average flowrate,split50%											
raw	0.0	0.00					0.00	7.00E+04	7.00E+04	9.00E+03	3.00E+03	1.60E+05	-	-
A	2.6	64.25					54.93	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	3.50E+01	-	-
B	2.0	128.49					109.85	4.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	1.00E+00	-	-
C	1.8	192.74					164.78 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	1.00E+00	-	-
D	1.5	256.98		28	14.51	0.85	219.71	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	1.00E+00	-	-
E	1.6	321.23					274.63 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	1.00E+00	-	-
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	2.6	64.25					54.93	-4.54E+00 >	-4.54E+00 >	-3.65E+00 >	-3.18E+00	-3.66E+00		
B	2.0	128.49					109.85	-4.24E+00 >	-4.54E+00 >	-3.65E+00 >	-3.18E+00	-5.20E+00		
C	1.8	192.74					164.78 >	-4.54E+00 >	-4.54E+00 >	-3.65E+00 >	-3.18E+00	-5.20E+00		
D	1.5	256.98					219.71	-4.54E+00 >	-4.54E+00 >	-3.65E+00 >	-3.18E+00 >	-5.20E+00		
E	1.6	321.23					274.63 >	-4.54E+00 >	-4.54E+00 >	-3.65E+00 >	-3.16E+00 >	-5.20E+00		
Data from Run 3 - 3/11/93 (EBB)														
	2,010 hrs	2.38	Average flowrate,split50%											
raw	0.0	0.00					0.00	1.10E+05	1.10E+04	3.00E+03	1.70E+03	contamination	-	-
A	2.8	61.40					59.14	1.30E+01	2.00E+00 <	2.00E+00 <	2.00E+00	contamination	-	-
B	2.4	122.81	3/9/93	2	3.69	0.96	118.26 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	contamination	-	-
C	2.1	184.21					177.42 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	contamination	-	-
D	1.4	245.62					236.55 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	contamination	-	-
E	2.0	307.02					295.69 <	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	contamination	-	-
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00			
A	2.8	61.40					59.14	-3.93E+00	-3.74E+00 >	-3.16E+00 >	-2.93E+00			
B	2.4	122.81					118.26 >	-4.74E+00 >	-3.74E+00 >	-3.16E+00 >	-2.93E+00			
C	2.1	184.21					177.42 >	-4.74E+00 >	-3.74E+00 >	-3.16E+00 >	-2.93E+00			
D	1.4	245.62					236.55 >	-4.74E+00 >	-3.74E+00 >	-3.16E+00 >	-2.93E+00			
E	2.0	307.02					295.69 >	-4.74E+00 >	-3.74E+00 >	-3.16E+00 >	-2.93E+00			

UV Bank	UV Int. Met. mW/cm2	UV Dose Mod mW*sec/cm2	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW*sec/cm2		Total Coliform MPN/100 mL		Fecal Coliform MPN/100 mL		Fecal Streptococci MPN/100 mL		Enterococci MPN/100 mL		HPC cfu/mL	MS2 pfu/mL	Polio pfu/100L
Data from Run 4 - 3/24/93 (EBB)																			
	2,322 hrs	2.13	Average flowrate,split50%																
raw	0.0	0.00					0.00		9.00E+04		1.70E+04		9.00E+03		1.70E+03		3.10E+04	-	-
A	2.4	66.99					60.90	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+01	-	-
B	1.8	133.98					121.79	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+00	-	-
C	1.8	200.97		15	9.10	0.91	182.69	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		1.00E+00	-	-
D	0.9	267.97					243.59	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+00	-	-
E	1.5	334.96					304.49	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	1.00E+00	-	-
Log N/No																			
raw	0.0	0.00					0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A	2.4	66.99					60.90	>	-4.65E+00	>	-3.93E+00	>	-3.65E+00	>	-2.93E+00	>	-3.49E+00		
B	1.8	133.98					121.79	>	-4.65E+00	>	-3.93E+00	>	-3.65E+00	>	-2.93E+00	>	-4.49E+00		
C	1.8	200.97					182.69	>	-4.65E+00	>	-3.93E+00	>	-3.65E+00	>	-2.93E+00		-4.49E+00		
D	0.9	267.97					243.59	>	-4.65E+00	>	-3.93E+00	>	-3.65E+00	>	-2.93E+00	>	-4.49E+00		
E	1.5	334.96					304.49	>	-4.65E+00	>	-3.93E+00	>	-3.65E+00	>	-2.93E+00	>	-4.49E+00		
Data from Run 5 - 4/28/93 (EBB) - Lamp Covered at 60%																			
	3,161 hrs	1.69	Average flowrate,split50%																
raw	0.0	0.00					0.00		6.00E+04		3.00E+04		1.40E+03		9.00E+02		4.00E+04	-	-
A	0.6	34.88					28.63		4.00E+00		6.00E+00	<	2.00E+00	<	2.00E+00		6.00E+01	-	-
B	1.3	69.75		50	23.66	0.76	53.25		2.00E+00		2.00E+00	<	2.00E+00	<	2.00E+00		2.00E+01	-	-
C	0.6	104.63					79.88	<	2.00E+00		2.00E+00	<	2.00E+00	<	2.00E+00		1.20E+01	-	-
D	0.1	139.51					106.50	<	2.00E+00	<	2.00E+00	<	2.00E+00	<	2.00E+00		1.60E+00	-	-
E	0.6	174.39					133.13	<	2.00E+00	<	2.00E+00		NA		NA		6.00E+00	-	-
Log N/No																			
raw	0.0	0.00					0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A	0.6	34.88					28.63		-4.30E+00		-3.57E+00	>	-2.65E+00	>	-2.65E+00		-2.70E+00		
B	1.3	69.75					53.25		-4.60E+00		-4.16E+00	>	-2.65E+00	>	-2.65E+00		-3.30E+00		
C	0.6	104.63					79.88	>	-4.60E+00		-4.16E+00	>	-2.65E+00	>	-2.65E+00		-3.52E+00		
D	0.1	139.51					106.50	>	-4.60E+00	>	-4.16E+00	>	-2.65E+00	>	-2.65E+00		-4.43E+00		
E	0.6	174.39					133.13	>	-4.60E+00	>	-4.16E+00						-3.62E+00		
Data from Run 6 - 5/13/93 (EBB) - Lamp Covered at 60%																			
	3,522 hrs	4.00	Avg																
raw	0.0	0.00					0.00		9.00E+04		8.00E+04		1.30E+03		2.70E+02		9.30E+04	-	-
A	0.4	14.67					10.42		1.30E+04		6.00E+03		2.40E+02		1.20E+01		7.30E+03	-	-
B	0.7	29.73					20.64		5.00E+03		3.00E+03		2.30E+01		2.30E+01		1.30E+03	-	-
C	0.6	44.60		65	29.90	0.70	31.26		2.30E+02		1.30E+02		4.00E+00		2.00E+00		4.00E+02	-	-
D	0.1	59.46					41.69		5.00E+01		8.00E+00	<	2.00E+00	<	2.00E+00		1.00E+02	-	-
E	0.4	74.33					52.11		3.00E+01		4.00E+00	<	2.00E+00	<	2.00E+00		3.90E+01	-	-
Log N/No																			
raw	0.0	0.00					0.00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00		
A	0.4	13.99					10.42		-6.40E-01		-1.00E+00		-7.34E-01		-1.35E+00		-1.11E+00		
B	0.7	27.96					20.64		-1.26E+00		-1.43E+00		-1.75E+00		-1.07E+00		-1.65E+00		
C	0.6	41.97					31.26		-2.59E+00		-2.79E+00		-2.51E+00		-2.13E+00		-2.37E+00		
D	0.1	55.97					41.69		-3.26E+00		-4.00E+00	>	-2.81E+00	>	-2.13E+00		-2.97E+00		
E	0.4	69.96					52.11		-3.48E+00		-4.30E+00	>	-2.81E+00	>	-2.13E+00		-3.36E+00		

UV Bank	UV Int. Met. mW/cm2	UV Dose Mod mW•sec/cm2	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/100L
Data from Run 7 - 5/19/93 (EBB) - Lamp Covered at 60%														
	3,666 hrs	3.90 avg												
raw	0.0	0.00					0.00	2.30E+04	2.30E+04	1.70E+03	1.70E+03	4.40E+04	-	-
A	0.1	15.27					10.32	6.00E+03	3.00E+03	1.30E+02	1.30E+02	4.60E+03	-	-
B	0.7	30.54		71	32.39	0.88	20.65	3.00E+03	6.00E+02	5.00E+01	5.00E+01	1.23E+03	-	-
C	0.5	45.81					30.97	3.00E+02	5.00E+01	< 2.00E+00	< 2.00E+00	2.70E+02	-	-
D	0.0	61.08					41.29	1.40E+02	8.00E+00	2.00E+00	< 2.00E+00	1.00E+02	-	-
E	0.3	76.35					51.82	1.70E+01	1.30E+01	< 2.00E+00	< 2.00E+00	5.00E+01	-	-
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	0.1	15.27					10.32	-6.63E-01	-8.85E-01	-1.12E+00	-1.12E+00	-9.81E-01		
B	0.7	30.54					20.65	-8.85E-01	-1.66E+00	-1.53E+00	-1.53E+00	-1.55E+00		
C	0.5	45.81					30.97	-1.88E+00	-2.66E+00 >	-2.93E+00 >	-2.93E+00	-2.21E+00		
D	0.0	61.08					41.29	-2.22E+00	-3.46E+00	-2.93E+00 >	-2.93E+00	-2.84E+00		
E	0.3	76.35					51.82	-3.13E+00	-3.25E+00 >	-2.93E+00 >	-2.93E+00	-2.94E+00		
Data from Run 8 - 5/26/93 (EBB) - Lamp Covered at 60%														
	3,830 hrs	4.00 avg												
raw	0.0	0.00					0.00	5.00E+04	1.10E+04	5.00E+03	2.20E+03	7.20E+04	-	-
A	0.2	14.87					9.62	2.40E+04	1.30E+04	5.00E+02	5.00E+02	9.30E+03	-	-
B	0.5	29.73		78	35.31	0.65	19.23	1.30E+04	5.00E+03	1.10E+02	1.10E+02	5.00E+03	-	-
C	0.4	44.60					28.85	1.10E+03	3.00E+02	2.00E+00	2.00E+00	8.80E+02	-	-
D	0.0	59.46					38.47	3.00E+02 <	2.00E+00 <	2.00E+00 <	2.00E+00	3.20E+02	-	-
E	0.4	74.33					48.09	5.00E+01	3.00E+01 <	2.00E+00 <	2.00E+00	1.30E+02	-	-
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	0.2	14.87					9.62	-3.19E-01	7.26E-02	-1.00E+00	-6.43E-01	-8.89E-01		
B	0.5	29.73					19.23	-5.85E-01	-3.42E-01	-1.66E+00	-1.30E+00	-1.16E+00		
C	0.4	44.60					28.85	-1.68E+00	-1.56E+00	-3.40E+00	-3.04E+00	-1.91E+00		
D	0.0	59.46					38.47	-2.22E+00 >	-3.74E+00 >	-3.40E+00 >	-3.04E+00	-2.35E+00		
E	0.4	74.33					48.09	-3.00E+00	-2.56E+00 >	-3.40E+00 >	-3.04E+00	-2.74E+00		
Data from Run 9 - 6/2/93 (JML/EBB/KRR) - Lamp Covered at 60% - MS2 Seeding														
	3,998 hrs	3.70 avg												
raw	0.0	0.00					0.00	2.20E+05	1.40E+05	2.80E+03	2.60E+03	8.30E+04	8.00E+04	-
A	0.1	14.54					8.99	3.00E+04	1.30E+04	2.40E+02	2.40E+02	2.50E+04	1.40E+04	-
B	0.5	29.09					17.97	1.10E+04	5.00E+03	2.40E+02	1.30E+02	1.10E+04	6.20E+03	-
C	0.1	43.63		85	38.22	0.62	26.96	1.10E+04 <	2.00E+00	5.00E+01	5.00E+01	5.60E+03	4.30E+03	-
D	0.0	58.18					35.94	6.00E+02 <	2.00E+00	6.00E+00	4.00E+00	1.40E+03	9.90E+02	-
E	0.2	72.72					44.93	2.30E+02 <	2.00E+00	6.00E+00	8.00E+00	5.60E+02	3.90E+02	-
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
A	0.1	14.54					8.99	-8.55E-01	-1.03E+00	-1.07E+00	-1.07E+00	-5.21E-01	-8.32E-01	
B	0.5	29.09					17.97	-1.30E+00	-1.45E+00	-1.07E+00	-1.33E+00	-6.78E-01	-9.86E-01	
C	0.1	43.63					26.96	-1.30E+00 >	-4.85E+00	-1.75E+00	-1.75E+00	-1.17E+00	-1.14E+00	
D	0.0	58.18					35.94	-2.44E+00 >	-4.85E+00	-2.54E+00	-2.85E+00	-1.77E+00	-1.78E+00	
E	0.2	72.72					44.93	-2.98E+00 >	-4.85E+00	-2.54E+00	-2.54E+00	-2.17E+00	-2.19E+00	

UV Bank	UV Int. Met. mW/cm2	UV Dose ModLamp mW•sec/cm2	Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/100L
Data from Run 16 - 7/21/93 (JML/EBB/KRR) - Lamp Covered at 60%														
	5,173 hrs	3.20	avg											
raw	0.0	0.00					0.00	8.00E+04	3.00E+04	3.00E+01	3.00E+01	2.60E+04	-	-
A	0.8	18.61					7.70	3.00E+04	8.00E+03	1.40E+02	1.10E+02	2.70E+03	-	-
B	2.8	37.22		134	58.60	0.41	15.41	8.00E+03	2.70E+03	5.00E+01	2.10E+01	1.50E+03	-	-
C	0.1	55.83					23.11	1.30E+03	1.30E+03	3.00E+01	3.00E+01	1.20E+03	-	-
D	2.4	74.44					30.82	2.30E+02	2.30E+02	< 2.00E+00	< 2.00E+00	1.80E+02	-	-
E	2.5	93.05					38.52	1.70E+01	2.30E+01	2.00E+00	2.00E+00	3.50E+01	-	-
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	0.8	18.61					7.70	-4.26E-01	-5.74E-01	6.69E-01	5.64E-01	-9.84E-01		
B	2.8	37.22					15.41	-1.00E+00	-1.05E+00	2.22E-01	-1.55E-01	-1.24E+00		
C	0.1	55.83					23.11	-1.79E+00	-1.36E+00	0.00E+00	0.00E+00	-1.34E+00		
D	2.4	74.44					30.82	-2.54E+00	-2.12E+00	> -1.18E+00	> -1.18E+00	-2.18E+00		
E	2.5	93.05					38.52	-3.87E+00	-3.12E+00	-1.18E+00	-1.18E+00	-2.87E+00		
Data from Run 17 - 7/27/93 (JML/EBB/KRR) - Lamp Covered at 60%														
	5,317 hrs	3.50	Average flowrate											
raw	0.0	0.00					0.00	8.00E+03	5.00E+03	2.40E+02	1.30E+02	2.10E+04	-	-
A	0.5	17.09					8.65	1.30E+04	8.00E+03	5.00E+01	5.00E+01	2.30E+03	-	-
B	2.2	34.18					13.30	2.30E+03	2.30E+03	4.00E+00	4.00E+00	6.40E+02	-	-
C	0.1	51.27		140	61.10	0.39	19.94	2.30E+02	1.30E+02	< 2.00E+00	< 2.00E+00	3.10E+02	-	-
D	2.2	68.36					26.59	4.00E+01	4.00E+01	2.00E+00	2.00E+00	9.30E+01	-	-
E	2.1	65.45					33.24	2.30E+01	4.00E+00	< 2.00E+00	< 2.00E+00	1.30E+02	-	-
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
A	0.5	17.09					8.65	2.11E-01	2.04E-01	-8.81E-01	-4.15E-01	-9.60E-01		
B	2.2	34.18					13.30	-5.41E-01	-3.37E-01	-1.78E+00	-1.51E+00	-1.52E+00		
C	0.1	51.27					19.94	-1.54E+00	-1.59E+00	> -2.08E+00	> -1.81E+00	-1.83E+00		
D	2.2	68.36					26.59	-2.30E+00	-2.10E+00	-2.08E+00	-1.81E+00	-2.35E+00		
E	2.1	65.45					33.24	-2.54E+00	-3.10E+00	> -2.08E+00	> -1.81E+00	-2.21E+00		

UV Bank	UV Int. Met. mW/cm2	UV Dose Mod mW•sec/cm2	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/100L
Data from Run 18 - 8/3/93 (JML/EBB/KRR) - Lamp Covered at 60% - MS2 and Polio seeding														
	5,469 hrs	3.10	avg											
raw	0.0	0.00					0.00	2.40E+05	3.00E+05	1.60E+03	1.60E+03	5.00E+04	2.00E+04	3.60E+04
A	0.0	18.73					6.74	3.00E+04	2.40E+04	1.70E+02	1.70E+02	6.10E+03	2.00E+04	2.70E+02
B	1.5	37.47		147	64.01	0.36	13.48	6.00E+03	5.00E+03	5.00E+01	5.00E+01	3.20E+03	2.50E+04	3.60E+01
C	0.0	56.20					20.23	1.70E+04	1.30E+04	3.00E+01	3.00E+01	1.80E+03	1.10E+04	-
D	1.5	74.93					26.97	5.00E+02	2.40E+02	4.00E+00	4.00E+00	3.30E+02	1.70E+03	2.70E+01
E	1.8	93.67					33.71	3.00E+02	3.00E+02	2.00E+00	2.00E+00	2.00E+02	8.00E+02	4.40E+00
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
A	0.0	18.73					6.74	-9.03E-01	-1.10E+00	-9.74E-01	-9.74E-01	-9.14E-01	0.00E+00	-2.12E+00
B	1.5	37.47					13.48	-1.48E+00	-1.78E+00	-1.51E+00	-1.51E+00	-1.19E+00	9.69E-02	-3.00E+00
C	0.0	56.20					20.23	-1.15E+00	-1.36E+00	-1.73E+00	-1.73E+00	-1.44E+00	-2.60E-01	-
D	1.5	74.93					26.97	-2.58E+00	-3.10E+00	-2.60E+00	-2.60E+00	-2.16E+00	-1.07E+00	-3.12E+00
E	1.8	93.67					33.71	-2.90E+00	-3.00E+00	-2.90E+00	-2.90E+00	-2.40E+00	-1.40E+00	-3.91E+00
Data from Run 19 - 9/14/93 (AW/LC/SA/EBB/KRR) - Lamp Covered at 60% - MS2 and Polio seeding														
	6,496 hrs	3.00	avg					GM		GM				GM
raw	0.0	0.00	9/8/93	8.0	5.35	0.95	0.00	8.04E+04	4.22E+04	2.40E+03	3.50E+02	5.90E+04	1.74E+05	4.90E+04
A	0.0	18.29					17.31	8.79E+02	5.59E+02	2.30E+01	2.30E+01	1.90E+03	5.16E+03	5.70E+02
B	1.0	36.57					34.61	7.83E+00	2.52E+00	< 2.00E+00	< 2.00E+00	2.10E+01	8.63E+02	1.10E+02
C	0.0	54.86					51.92	2.03E+00	2.03E+00	< 2.00E+00	< 2.00E+00	1.10E+01	2.90E+02	8.10E+00
D	1.5	73.14					69.23	2.00E+00	2.52E+00	2.00E+00	< 2.00E+00	3.00E+01	4.88E+01	8.00E-01
E	2.0	91.43					86.53	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	4.10E+01	< 1.00E+00	3.90E+00
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
A	0.0	18.29					17.31	-1.96E+00	-1.88E+00	-2.02E+00	-1.18E+00	-1.49E+00	-1.53E+00	-1.93E+00
B	1.0	36.57					34.61	-4.01E+00	-4.22E+00	> -3.08E+00	> -2.24E+00	-3.45E+00	-2.42E+00	-2.65E+00
C	0.0	54.86					51.92	-4.60E+00	-4.32E+00	> -3.08E+00	> -2.24E+00	-3.73E+00	-2.78E+00	-3.90E+00
D	1.5	73.14					69.23	-4.60E+00	-4.22E+00	-3.08E+00	> -2.24E+00	-3.29E+00	-3.55E+00	-4.91E+00
E	2.0	91.43					86.53	> -4.60E+00	> -4.32E+00	> -3.08E+00	> -2.24E+00	-3.15E+00	> -5.24E+00	-4.10E+00

UV Bank	UV Int. Met. mW/cm2	UV Dose Mod mW•sec/cm2	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/100L
Data from Run 20 - 9/23/93 (AW/LC/SA/EBB/KRR) - Lamp Covered at 60% - MS2 and Polio seeding														
	6,713 hrs	3.40	Average flowrate					GM	GM				GM	
raw	0.0	0.00					0.00	1.11E+04	4.93E+03	1.10E+01	1.10E+01	7.00E+03	4.44E+04	2.70E+03
A	0.0	18.08		15.0	9.10	0.91	14.82	2.33E+03	4.29E+02	4.00E+00	4.00E+00	1.00E+03	1.80E+04	4.10E+02
B	0.8	32.17					29.24	6.59E+02	1.93E+02	< 2.00E+00	< 2.00E+00	2.60E+02	4.26E+03	1.20E+02
C	0.0	48.25					43.88	1.88E+01	2.52E+00	< 2.00E+00	< 2.00E+00	2.20E+02	4.79E+02	1.20E+00
D	1.2	64.33					58.48	2.05E+01	5.80E+00	< 2.00E+00	< 2.00E+00	9.70E+02	5.55E+01	0.00E+00
E	1.8	80.42					73.10	3.17E+00	2.52E+00	< 2.00E+00	< 2.00E+00	2.30E+02	2.20E+01	0.00E+00
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
A	0.0	18.08					14.82	-6.78E-01	-1.06E+00	-4.39E-01	-4.39E-01	-8.45E-01	-4.43E-01	-8.19E-01
B	0.8	32.17					29.24	-1.30E+00	-1.41E+00	> -7.40E-01	> -7.40E-01	-1.43E+00	-1.02E+00	-1.35E+00
C	0.0	48.25					43.88	-2.77E+00	-3.29E+00	> -7.40E-01	> -7.40E-01	-1.50E+00	-1.97E+00	-3.35E+00
D	1.2	64.33					58.48	-2.73E+00	-2.94E+00	> -7.40E-01	> -7.40E-01	-8.58E-01	-2.90E+00	#NUM!
E	1.8	80.42					73.10	-3.54E+00	-3.29E+00	> -7.40E-01	> -7.40E-01	-1.48E+00	-3.30E+00	#NUM!
Data from Run 21 - 9/29/93 - Lamp Covered at 60%? - MS2 and Polio seeding														
	6852 hrs	3.38	avg					GM	GM					
raw	0.0	0.00					0.00	2.19E+04	1.14E+04	3.00E+02	1.70E+02	1.70E+04	1.90E+05	2.70E+04
A	0.0	14.94					13.21	9.25E+03	2.33E+03	8.00E+01	1.70E+01	3.10E+03	1.00E+05	1.40E+04
B	0.5	29.88		21.0	11.59	0.88	28.42	4.45E+03	3.44E+03	8.00E+01	2.70E+01	2.70E+03	6.50E+04	4.70E+03
C	0.0	44.82					39.62	7.11E+02	2.27E+02	4.00E+00	2.00E+00	4.70E+02	1.50E+04	1.50E+02
D	0.8	59.76					52.83	1.45E+01	4.31E+00	< 2.00E+00	< 2.00E+00	6.00E+02	9.90E+02	3.70E+00
E	1.4	74.70					66.04	2.00E+00	2.00E+00	< 2.00E+00	< 2.00E+00	6.00E+02	1.80E+02	1.80E+00
Log N/No														
raw	0.0	0.00					0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
A	0.0	14.94					13.21	-3.74E-01	-6.91E-01	-5.74E-01	-1.00E+00	-7.39E-01	-2.79E-01	-2.65E-01
B	0.5	29.88					26.42	-6.92E-01	-5.21E-01	-5.74E-01	-7.99E-01	-7.99E-01	-4.66E-01	-7.59E-01
C	0.0	44.82					39.62	-1.49E+00	-1.70E+00	-1.88E+00	-1.93E+00	-1.56E+00	-1.10E+00	-2.26E+00
D	0.8	59.76					52.83	-3.18E+00	-3.42E+00	> -2.18E+00	> -1.93E+00	-1.33E+00	-2.28E+00	-3.68E+00
E	1.4	74.70					66.04	-4.04E+00	-3.76E+00	> -2.18E+00	> -1.93E+00	-1.45E+00	-3.02E+00	-4.18E+00
Data from Run 22 - 11/10/93 - Lamp uncovered - Full Flow														
	7,860 hrs	3.15	Avg flowrate											
raw	0.0	0.00					0.00	8.00E+04	1.70E+04					
A		40.02					35.38	4.00E+00	< 2.00E+00					
B		80.04	11/9/93	1.0	3.27	0.97	70.76	< 2.00E+00	< 2.00E+00					
C		120.05					106.14	< 2.00E+00	< 2.00E+00					
D		160.07					141.51	< 2.00E+00	< 2.00E+00	<	<			
E		200.09					176.89	< 2.00E+00	< 2.00E+00	<	<			
Log N/No														
raw		0.00					0.00	0.00E+00	0.00E+00	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!
A		40.02					35.38	-4.30E+00	> -3.93E+00	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!
B		80.04					70.76	> -4.60E+00	> -3.93E+00	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!
C		120.05					106.14	> -4.60E+00	> -3.93E+00	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!
D		160.07					141.51	> -4.60E+00	> -3.93E+00	> #NUM!	> #NUM!	#NUM!	#NUM!	#NUM!

UV Bank	UV Int. mW/cm2	Met. UV Dose mW•sec/cm2	Mod	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2		Total Coliform MPN/100 mL		Fecal Coliform MPN/100 mL		Fecal Streptococci MPN/100 mL		Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/100L
E		200.09						176.89	>	4.60E+00	>	3.93E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
Data from Run 23 - 11/11/93 - Lamp uncovered - Full Flow																			
	7,884 hrs	3.15		Avg flowrate															
raw	0.0	0.00						0.00		5.00E+05		1.70E+04							
A		40.02						38.54		8.00E+00		2.00E+00							
B		80.04		11/9/93	2.0	3.69	0.96	77.08	<	2.00E+00	<	2.00E+00							
C		120.05						115.62	<	2.00E+00	<	2.00E+00							
D		160.07						154.17		2.00E+00		2.00E+00	<		<				
E		200.09						192.71	<	2.00E+00	<	2.00E+00	<		<				
Log N/No																			
raw		0.00						0.00		0.00E+00		0.00E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
A		40.02						38.54		4.80E+00		3.93E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
B		80.04						77.08	>	5.40E+00	>	3.93E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
C		120.05						115.62	>	5.40E+00	>	3.93E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
D		160.07						154.17		5.40E+00		3.93E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
E		200.09						192.71	>	5.40E+00	>	3.93E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
Data from Run 24 - 11/12/93 - Lamp uncovered - Full Flow																			
	7,908 hrs	3.15		Avg flowrate															
raw	0.0	0.00						0.00		8.00E+04		8.00E+04							
A		39.33						37.71		2.30E+01		2.00E+00							
B		78.86		11/9/93	3.0	4.11	0.96	75.43	<	2.00E+00	<	2.00E+00							
C		117.98						113.14	<	2.00E+00	<	2.00E+00							
D		157.31						150.85	<	2.00E+00	<	2.00E+00	<		<				
E		196.84						188.57	<	2.00E+00	<	2.00E+00	<		<				
Log N/No																			
raw		0.00						0.00		0.00E+00		0.00E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
A		39.33						37.71		3.54E+00		4.80E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
B		78.86						75.43	>	4.80E+00	>	4.80E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
C		117.98						113.14	>	4.80E+00	>	4.80E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
D		157.31						150.85	>	4.80E+00	>	4.80E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
E		196.84						188.57	>	4.80E+00	>	4.80E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
Data from Run 25 - 11/13/93 - Lamp uncovered - Full Flow																			
	7,932 hrs	3.15		Avg flowrate															
raw	0.0	0.00						0.00		2.30E+04		3.00E+04							
A		40.02						38.21	<	2.00E+00	<	2.00E+00							
B		80.04		11/9/93	4.0	4.52	0.95	76.42	<	2.00E+00	<	2.00E+00							
C		120.05						114.63	<	2.00E+00	<	2.00E+00							
D		160.07						152.83		2.00E+00	<	2.00E+00	<		<				
E		200.09						191.04	<	2.00E+00	<	2.00E+00	<		<				

UV Bank	UV Int. Met. mW/cm2	UV Dose Mod mW•sec/cm2	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2		Total Coliform MPN/100 mL		Fecal Coliform MPN/100 mL		Fecal Streptococci MPN/100 mL		Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/100L
Log N/No																		
raw		0.00					0.00		0.00E+00		0.00E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
A		40.02					36.21	>	-4.06E+00	>	-4.18E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
B		80.04					76.42	>	-4.06E+00	>	-4.18E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
C		120.05					114.63	>	-4.06E+00	>	-4.18E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
D		160.07					152.83		-4.06E+00	>	-4.18E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
E		200.09					191.04	>	-4.06E+00	>	-4.18E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
Data from Run 26 - 11/14/93 - Lamp uncovered - Full Flow																		
	7,956 hrs	3.15	Avg flowrate															
raw	0.0	0.00					0.00		9.00E+04		2.30E+04							
A		40.02					38.04		1.70E+01		1.10E+01							
B		60.04	11/9/93	5.0	4.94	0.95	76.08	<	2.00E+00	<	2.00E+00							
C		120.05					114.13	<	2.00E+00	<	2.00E+00							
D		160.07					152.17	<	2.00E+00	<	2.00E+00	<		<				
E		200.09					190.21	<	2.00E+00	<	2.00E+00	<		<				
Log N/No																		
raw		0.00					0.00		0.00E+00		0.00E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
A		40.02					38.04		-3.72E+00		-3.32E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
B		80.04					76.08	>	-4.65E+00	>	-4.06E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
C		120.05					114.13	>	-4.65E+00	>	-4.06E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
D		160.07					152.17	>	-4.65E+00	>	-4.08E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
E		200.09					190.21	>	-4.65E+00	>	-4.06E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
Data from Run 27 - 11/15/93 - Lamp uncovered - Full Flow																		
	7,980 hrs	3.15	Avg flowrate															
raw	0.0	0.00					0.00		5.00E+04		2.30E+04							
A		40.02					37.88		2.00E+00		2.00E+00							
B		80.04	11/9/93	8.0	5.35	0.95	75.75		8.00E+00		2.00E+00							
C		120.05					113.63	<	2.00E+00	<	2.00E+00							
D		160.07					151.50	<	2.00E+00	<	2.00E+00	<		<				
E		200.09					189.38	<	2.00E+00	<	2.00E+00	<		<				
Log N/No																		
raw		0.00					0.00		0.00E+00		0.00E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
A		40.02					37.88		-4.40E+00		-4.06E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
B		80.04					75.75		-3.80E+00		-4.06E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
C		120.05					113.63	>	-4.40E+00	>	-4.06E+00		#NUM!		#NUM!	#NUM!	#NUM!	#NUM!
D		160.07					151.50	>	-4.40E+00	>	-4.06E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
E		200.09					189.38	>	-4.40E+00	>	-4.06E+00	>	#NUM!	>	#NUM!	#NUM!	#NUM!	#NUM!
Data from Run 28 - 11/16/93 - Lamp uncovered - Full Flow																		

UV Bank	UV Int. Mat. mW/cm2	UV Dose Mod mW•sec/cm2	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2		Total Coliform MPN/100 mL		Fecal Coliform MPN/100 mL		Fecal Streptococci MPN/100 mL		Enterococci MPN/100 mL		HPC cfu/mL		MS2 pfu/mL	Polio pfu/100L
	8,004 hrs	3.15	Avg flowrate																	
raw	0.0	0.00					0.00		1.30E+02		7.00E+00								1.00E+03	
A		39.33					37.06		2.60E+01		4.00E+00								2.20E+02	
B		78.66	11/9/93	7.0	5.77	0.94	74.12		1.10E+00	<	2.00E+00								2.20E+01	
C		117.98					111.18	<	2.00E+00	<	2.00E+00								5.00E+00	
D		157.31					148.24		2.00E+00		2.00E+00	<		<				<	1.00E+02	
E		196.64					185.30	<	2.00E+00	<	2.00E+00	<		<				<	1.00E+02	
Log N/No																				
raw		0.00					0.00		0.00E+00		0.00E+00		#NUM!		#NUM!		#NUM!		0.00E+00	#NUM!
A		39.33					37.06		-6.99E-01		-2.43E-01		#NUM!		#NUM!		#NUM!		-6.58E-01	#NUM!
B		78.66					74.12		-2.07E+00	>	-5.44E-01		#NUM!		#NUM!		#NUM!		-1.66E+00	#NUM!
C		117.98					111.18	>	-1.81E+00	>	-5.44E-01		#NUM!		#NUM!		#NUM!		-2.30E+00	#NUM!
D		157.31					148.24		-1.81E+00		-5.44E-01	>	#NUM!	>	#NUM!		#NUM!	>	-1.00E+00	#NUM!
E		196.64					185.30	>	-1.81E+00	>	-5.44E-01	>	#NUM!	>	#NUM!		#NUM!	>	-1.00E+00	#NUM!
Data from Run 29 - 11/17/93 - Lamp uncovered - Full Flow																				
	8,028 hrs	3.15	Avg flowrate																	
raw	0.0	0.00					0.00		1.30E+04		5.00E+03								1.00E+03	
A		40.02					37.54		2.00E+00		2.00E+00								2.20E+02	
B		80.04	11/9/93	8.0	6.19	0.94	75.09	<	2.00E+00	<	2.00E+00								2.20E+01	
C		120.05					112.63	<	2.00E+00	<	2.00E+00								5.00E+00	
D		160.07					150.17	<	2.00E+00	<	2.00E+00	<		<				<	1.00E+02	
E		200.09					187.71	<	2.00E+00	<	2.00E+00	<		<				<	1.00E+02	
Log N/No																				
raw		0.00					0.00		0.00E+00		0.00E+00		#NUM!		#NUM!		#NUM!		0.00E+00	#NUM!
A		40.02					37.54		-3.81E+00		-3.40E+00		#NUM!		#NUM!		#NUM!		-6.56E-01	#NUM!
B		80.04					75.09	>	-3.81E+00	>	-3.40E+00		#NUM!		#NUM!		#NUM!		-1.66E+00	#NUM!
C		120.05					112.63	>	-3.81E+00	>	-3.40E+00		#NUM!		#NUM!		#NUM!		-2.30E+00	#NUM!
D		160.07					150.17	>	-3.81E+00	>	-3.40E+00	>	#NUM!	>	#NUM!		#NUM!	>	-1.00E+00	#NUM!
E		200.09					187.71	>	-3.81E+00	>	-3.40E+00	>	#NUM!	>	#NUM!		#NUM!	>	-1.00E+00	#NUM!
Data from Run 30 - 11/18/93 - Lamp uncovered - Full Flow																				
	8,052 hrs	3.15	Avg flowrate																	
raw	0.0	0.00					0.00		2.20E+04		1.40E+04								1.00E+03	
A		40.02					37.36	<	2.00E+00	<	2.00E+00								2.20E+02	
B		80.04	11/9/93	9.0	6.60	0.93	74.75	<	2.00E+00	<	2.00E+00								2.20E+01	
C		120.05					112.13	<	2.00E+00	<	2.00E+00								5.00E+00	
D		160.07					149.50		2.00E+00		2.00E+00	<		<				<	1.00E+02	
E		200.09					186.88	<	2.00E+00	<	2.00E+00	<		<				<	1.00E+02	
Log N/No																				

UV Bank	UV Int. Met. mW/cm2	UV Dose Mod mW•sec/cm2	Lamp Clean Date	Lamp Oper. Day	% Lamp Fouling	Correction Factor	Adj. UV Dose mW•sec/cm2		Total Coliform MPN/100 mL		Fecal Coliform MPN/100 mL		Fecal Streptococci MPN/100 mL		Enterococci MPN/100 mL		HPC cfu/mL		MS2 pfu/mL	Polio pfu/100L
raw		0.00					0.00		0.00E+00		0.00E+00		#NUM!		#NUM!		#NUM!		0.00E+00	#NUM!
A		40.02					37.38	>	-4.04E+00	>	-3.85E+00		#NUM!		#NUM!		#NUM!		-6.58E-01	#NUM!
B		80.04					74.75	>	-4.04E+00	>	-3.85E+00		#NUM!		#NUM!		#NUM!		-1.68E+00	#NUM!
C		120.05					112.13	>	-4.04E+00	>	-3.85E+00		#NUM!		#NUM!		#NUM!		-2.30E+00	#NUM!
D		160.07					149.50		-4.04E+00		-3.85E+00	>	#NUM!	>	#NUM!		#NUM!	>	-1.00E+00	#NUM!
E		200.09					186.88	>	-4.04E+00	>	-3.85E+00	>	#NUM!	>	#NUM!		#NUM!	>	-1.00E+00	#NUM!

Cl Sample	Chlorine Dose, mg/L	Chlorine Free, mg/L	Chlorine Total, mg/L	Chlorine Comb., mg/L	Time min	CT min•mg/L	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC clu/mL	MS2 plu/mL	Polio plu/mL
Data from Run 2 - 11/3/92 (JML)													
raw	0.00	0.00	0.00	0.00		0.0	2.30E+05	3.00E+04	1.30E+03	2.00E+02	9.60E+04	4.00E+04	
ctrl	0.00	0.00	0.00	0.00		0.0	2.40E+05	5.00E+04	2.20E+03	1.70E+03	9.50E+04	4.60E+04	
1	0.50	0.15	0.20	0.05		18.0	5.00E+04	5.00E+03	8.00E+01	8.00E+01	1.60E+04	1.40E+04	
2	1.50	0.25	0.55	0.30		30.0	2.40E+02	< 2.00E+00	2.00E+00	2.00E+00	1.20E+02	< 1.00E+00	
3	2.50	0.30	0.80	0.30		38.0	2.30E+01	< 2.00E+00	< 2.00E+00	< 2.00E+00	9.00E+00	< 1.00E+00	
4	5.10	1.20	1.95	0.75		144.0	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	4.00E+00	< 1.00E+00	
5	7.80	2.80	3.80	0.80		336.0	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	1.50E+00	< 1.00E+00	
Log N/No													
raw	0.00	0.00	0.00	0.00		0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
ctrl	0.00	0.00	0.00	0.00		0.0	1.85E-02	2.22E-01	2.28E-01	9.29E-01	-4.55E-03	6.07E-02	
1	0.50	0.15	0.20	0.05		18.0	-6.63E-01	-7.78E-01	-1.21E+00	-3.98E-01	-7.76E-01	-4.56E-01	
2	1.50	0.25	0.55	0.30		30.0	-2.98E+00	> -4.18E+00	-2.81E+00	-2.00E+00	-2.90E+00	> -4.60E+00	
3	2.50	0.30	0.80	0.30		38.0	-4.00E+00	> -4.18E+00	> -2.81E+00	> -2.00E+00	-4.03E+00	> -4.60E+00	
4	5.10	1.20	1.95	0.75		144.0	> -5.06E+00	> -4.18E+00	> -2.81E+00	> -2.00E+00	-4.38E+00	> -4.60E+00	
5	7.80	2.80	3.80	0.80		336.0	> -5.08E+00	> -4.18E+00	> -2.81E+00	> -2.00E+00	-4.81E+00	> -4.60E+00	
Data from Run 3 - 1/4/93 (JML)													
raw	0.00	0.00	0.00	0.00		0.0	7.00E+04	7.00E+03	8.00E+02	1.70E+02	1.50E+05	2.10E+04	
ctrl	0.00	0.00	0.00	0.00		0.0	2.80E+04	3.00E+03	2.40E+03	2.70E+02	1.60E+05	9.50E+03	
1	1.00	0.00	0.34	0.34		0.0	< 2.00E+00	< 2.00E+00	2.00E+00	8.90E+02	< 1.00E+01		
2	2.00	0.05	0.34	0.29		8.0	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	1.80E+01	< 1.00E+00	
3	3.00	0.39	0.83	0.44		46.8	2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	1.50E+02	< 1.00E+00	
4	4.00	0.98	1.42	0.44		117.6	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 1.00E+01	< 1.00E+00	
5	5.00	1.87	2.36	0.49		224.4	< 2.00E+00	< 2.00E+00	< 2.00E+00	< 2.00E+00	5.40E+01	< 1.00E+00	
Log N/No													
raw	0.00	0.00	0.00	0.00		0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
ctrl	0.00	0.00	0.00	0.00		0.0	-3.98E-01	-3.68E-01	4.77E-01	2.01E-01	2.60E-02	-3.44E-01	
1	1.00	0.00	0.34	0.34		0.0	> -4.54E+00	> -3.54E+00	-2.80E+00	-1.93E+00	-2.23E+00	> -3.32E+00	
2	2.00	0.05	0.34	0.29		6.0	> -4.54E+00	> -3.54E+00	> -2.60E+00	> -1.93E+00	-3.92E+00	> -4.32E+00	
3	3.00	0.39	0.83	0.44		46.8	-4.54E+00	> -3.54E+00	> -2.60E+00	> -1.93E+00	-3.00E+00	> -4.32E+00	
4	4.00	0.98	1.42	0.44		117.6	> -4.54E+00	> -3.54E+00	> -2.60E+00	> -1.93E+00	> -4.16E+00	> -4.32E+00	
5	5.00	1.87	2.36	0.49		224.4	> -4.54E+00	> -3.54E+00	> -2.60E+00	> -1.93E+00	-3.44E+00	> -4.32E+00	

Cl Sample	Chlorine Dose, mg/L	Chlorine Free, mg/L	Chlorine Total, mg/L	Chlorine Comb., mg/L	Time min	CT min•mg/L	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/mL
Data from Run 4 - 1/11/93 (JML)													
raw	0.00	0.00	0.00	0.00		0.0	2.40E+04	8.00E+03	2.40E+03	2.40E+03	9.10E+04	2.30E+04	
ctrl	0.00	0.00	0.00	0.00		0.0	3.50E+04	1.30E+04	8.00E+02	3.00E+02	1.00E+05	3.60E+04	
1	0.50	0.00	0.15	0.15		0.0	5.00E+01	3.00E+01	2.00E+00 <	2.00E+00	5.80E+03	7.00E+03	
2	1.00	0.00	0.25	0.25		0.0	2.30E+01	8.00E+00 <	2.00E+00 <	2.00E+00	1.40E+03	5.00E+00	
3	1.50	0.00	0.29	0.29		0.0	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	1.40E+02	< 1.00E+00	
4	2.00	0.00	0.29	0.29		0.0	2.00E+00 <	2.00E+00 <	2.00E+00 <	2.00E+00	5.60E+01	< 1.00E+00	
5	4.00	1.03	1.32	0.29		123.6	2.00E+00	2.00E+00 <	2.00E+00 <	2.00E+00	8.00E+00	< 1.00E+00	
Log N/No													
raw	0.00	0.00	0.00	0.00		0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
ctrl	0.00	0.00	0.00	0.00		0.0	1.64E-01	2.11E-01	-4.77E-01	-9.03E-01	4.10E-02	1.95E-01	
1	0.50	0.00	0.15	0.15		0.0	-2.68E+00	-2.43E+00	-3.08E+00 >	-3.08E+00	-1.20E+00	-5.17E-01	
2	1.00	0.00	0.25	0.25		0.0	-3.02E+00	-3.00E+00 >	-3.08E+00 >	-3.08E+00	-1.81E+00	-3.66E+00	
3	1.50	0.00	0.29	0.29		0.0	-4.08E+00 >	-3.60E+00 >	-3.08E+00 >	-3.08E+00	-2.81E+00	> -4.36E+00	
4	2.00	0.00	0.29	0.29		0.0	-4.08E+00 >	-3.60E+00 >	-3.08E+00 >	-3.08E+00	-3.21E+00	> -4.36E+00	
5	4.00	1.03	1.32	0.29		123.6	-4.08E+00	-3.60E+00 >	-3.08E+00 >	-3.08E+00	-4.06E+00	> -4.36E+00	
Data from Run 5 - 1/19/93 (SAE)													
raw	0.00	0.00	0.00	0.00		0.0	8.00E+04	3.00E+04	2.40E+03	2.40E+03	1.15E+05	3.75E+04	
ctrl	0.00	0.00	0.00	0.00		0.0	8.00E+02	1.10E+02	3000?	3000?	8.20E+04	6.00E+04	
1	0.50	0.00	0.20	0.20		0.0	7.00E+02	3.00E+01 <	2.00E+00 <	2.00E+00	5.40E+03	3.55E+03	
2	1.00	0.00	0.25	0.25		0.0	8.00E+01	4.00E+00 <	2.00E+00 <	2.00E+00	8.60E+02	< 1.00E+00	
3	1.50	0.00	0.30	0.30		0.0	2.30E+01	2.30E+01 <	2.00E+00 <	2.00E+00	1.00E+02	< 1.00E+00	
4	2.00	0.05	0.49	0.44		6.0	2.00E+01	7.00E+00 <	2.00E+00 <	2.00E+00	7.60E+01	< 1.00E+00	
5	4.00	1.24	1.78	0.54		148.8	3.00E+01	8.00E+00 <	2.00E+00 <	2.00E+00	2.70E+01	< 1.00E+00	
Log N/No													
raw	0.00	0.00	0.00	0.00		0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
ctrl	0.00	0.00	0.00	0.00		0.0	-2.00E+00	-2.44E+00	#VALUE!	#VALUE!	-1.47E-01	2.04E-01	
1	0.50	0.00	0.20	0.20		0.0	-2.06E+00	-3.00E+00 >	-3.08E+00 >	-3.08E+00	-1.33E+00	-1.02E+00	
2	1.00	0.00	0.25	0.25		0.0	-3.00E+00	-3.88E+00 >	-3.08E+00 >	-3.08E+00	-2.13E+00	> -4.57E+00	
3	1.50	0.00	0.30	0.30		0.0	-3.54E+00	-3.12E+00 >	-3.08E+00 >	-3.08E+00	-3.06E+00	> -4.57E+00	
4	2.00	0.05	0.49	0.44		6.0	-3.60E+00	-3.63E+00 >	-3.08E+00 >	-3.08E+00	-3.18E+00	> -4.57E+00	
5	4.00	1.24	1.78	0.54		148.8	-3.43E+00	-3.57E+00 >	-3.08E+00 >	-3.08E+00	-3.63E+00	> -4.57E+00	

BENCH-SCALE CHLORINE DATA

Cl Sample	Chlorine Dose, mg/L	Chlorine Free, mg/L	Chlorine Total, mg/L	Chlorine Comb., mg/L	Time min	CT min•mg/L	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/mL
Data from Run 6 -3/2/93 (JML) ALL DATA NEED TO BE VERIFIED													
raw	0	0.00	0.00	0 00	0	0 0	2.30E+04	2 30E+04	-	-	-	5 40E+04	3 50E+04
ctrl	0	0.00	0.00	0.00	0	0 0	5.00E+03	2.30E+03	-	-	-	2 60E+04	6 00E+04
Cl-1a	-	-	-	-	-	-	5.00E+02	8.00E+02	-	-	-	1 60E+03	
Cl-2a	-	-	-	-	-	-	< 2.00E+00	< 2.00E+00	-	-	-	1 90E+03	
Cl-3a	-	-	-	-	-	-	7.00E+01	1.40E+02	-	-	-	1 90E+03	
Cl-1b/TC	10	0.34	4.56	4.22	30	10 2	2.00E+01	< 2.00E+00	-	-	-	-	-
Cl-2b/TC	10	0.34	4.56	4.22	40	13.6	4.00E+01	2.00E+01	-	-	-	-	-
Cl-3b/TC	10	0.20	4.38	4.18	60	12.0	?	2.00E+00	-	-	-	-	-
Cl-4b/TC	10	0.10	4.13	4.03	90	9.0	2.30E+01	2.00E+00	-	-	-	-	-
Cl-1b/MS2	10	0.98	5.01	4.03	10	9.8	-	-	-	-	-	< 1 00E+00	-
Cl-2b/MS2	10	0.69	4.82	4.13	20	13.8	-	-	-	-	-	< 1 00E+00	-
Cl-3b/MS2	10	0.34	4.56	4.22	30	10.2	-	-	-	-	-	< 1 00E+00	-
Cl-4b/MS2	10	0.20	4.38	4.18	60	12.0	-	-	-	-	-	< 1 00E+00	-
Cl-5/10	5	0 10	2 36	2.26	10	1.0	-	-	-	-		-	# 5.50E+03
Cl-5/20	5	0 05	2.36	2.31	20	1.0	-	-	-	-		-	# 5.50E+02
Cl-5/30	5	0 00	2 31	2.31	30	0 0	-	-	-	-		-	> 1 00E+00
Cl-10/20	10	0 69	4.82	4.13	20	13.8	-	-	-	-		-	> 1 00E+00
Cl-10/30	10												> 1 00E+00
CL-10/40	10	0.34	4.56	4.22	40	13.6	-	-	-	-		-	> 1 00E+00
CL-10/60	10	0.20	4.36	4.18	60	12.0	-	-	-	-		-	> 1.00E+00
CL-10/90	10.00	0.10	4.13	4.03	90	9.0	-	-	-	-		-	
Log N/No													
raw	0.00	0.00	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	-	-	-	0.00E+00	0 00E+00
ctrl	0.00	0.00 #	0.00	0.00	0.00	0.00	-6.63E-01	-1.00E+00	-	-	-	-3 17E-01	2 34E-01
Cl-1a	-	- #	-	-	-	-	-1.66E+00	-1.46E+00	-	-	-	-1.53E+00	#NUM!
Cl-2a	-	- #	-	-	-	-	> -4.06E+00	> -4.06E+00	-	-	-	-1 45E+00	#NUM!
Cl-3a	-	- #	-	-	-	-	-2.52E+00	-2.22E+00	-	-	-	-1.45E+00	#NUM!
Cl-1b/TC	10.00	0.98 #	5.01	4.03	30.00	10.20	-3.06E+00	-4.06E+00	-	-	-	> -4.73E+00	#VALUE!
Cl-2b/TC	10.00	0.34	4.56	4.22	40.00	13.60	-2.76E+00						
Cl-3b/TC	10.00 #	0.20	4.38	4.18	60.00	12.00	#VALUE!						
Cl-4b/TC	10.00 #	0.10	4.13	4.03	90.00	9.00	-3.00E+00						
Cl-1b/MS2	10.00	0.10 #	2.36	2.26	10.00	9.80	-	-	-	-	#VALUE!	#NUM!	#VALUE!
Cl-2b/MS2	10.00	0.69	4.82	4.13	20.00	13.80	-	-	-	-			
Cl-3b/MS2	10.00 #	0.34 #	4.56	4.22	30.00	10.20	-	-	-	-			
Cl-4b/MS2	10.00 #	0.20 #	4.38	4.18	60.00	12.00	-	-	-	-			
Cl-5/10	5.00	0.10	2.36	2.26	10.00	1.00	-	-	-	-			
Cl-5/20	5.00 #	0.05	2 36	2 31	20.00	1.00	-	-	-	-			
Cl-5/30	5 00 #	0 00 #	2 31	2 31	30 00	0 00	-	-	-	-	# #REF!	# #REF!	# #REF!

BENCH-SCALE CHLORINE DATA

Cl Sample	Chlorine Dose, mg/L	Chlorine Free, mg/L	Chlorine Total, mg/L	Chlorine Comb., mg/L	Time min	CT min•mg/L	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/mL
Cl 10/20	10.00	0.69	4.82	4.13	20.00	13.80	-	-	-	-			
Cl-10/30	10 00	0.00	0.00	0.00	0.00	0.00							
CL-10/40	10.00	0.34	4.56	4.22	40.00	13.60	-	-	-	-			
CL-10/60	10.00	0.20	4.38	4.18	60.00	12.00	-	-	-	-			
CL-10/90	10.00	0.10	4.13	4.03	90.00	9.00	-	-	-	-			

Cl Sample	Chlorine Dose, mg/L	Chlorine Free, mg/L	Chlorine Total, mg/L	Chlorine Comb., mg/L	Time min	CT min•mg/L	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 plu/mL	Polio plu/mL
Data from Run 7 - 5/4/93 (JML)													
raw	0.00	0.00	< 0.20	< 0.20	0	0.0	< 2.00E+00	< 2.00E+00	-	-	-	4.00E+04	1.60E+03
ctrl	0.00	0.00	0.00	0.00	0	0.0	2.00E+02	< 2.00E+00	-	-	-	3.80E+04	1.30E+03
CL-10/120	10.00	7.70	7.90	0.20	120	924.0	< 2.00E+00	< 2.00E+00	-	-	-	< 1.00E+00	-
CL-20/5	20.00	0.15	12.18	12.03	5	0.8	2.00E+01	2.00E+01	-	-	-	2.20E+03	2.30E+04
CL-20/15	20.00	0.05	12.38	12.33	15	0.8	< 2.00E+00	< 2.00E+00	-	-	-	2.10E+03	2.90E+04
Log N/No													
raw	0.00	0.00	> 0.20	> 0.20	0	0	> 0.00E+00	> 0.00E+00			#VALUE!	0.00E+00	0.00E+00
ctrl	0.00	0.00	0.00	0.00	0	0	2.00E+00	> 0.00E+00			#VALUE!	-2.23E-02	-9.02E-02
CL-10/120	10.00	7.70	7.90	0.20	120	924	> 0.00E+00	> 0.00E+00			#VALUE!	> -4.60E+00	
CL-20/5	20.00	0.15	12.18	12.03	5	0.75	1.00E+00	1.00E+00			#VALUE!	-1.26E+00	1.16E+00
CL-20/15	20.00	0.05	12.38	12.33	15	0.75	> 0.00E+00	> 0.00E+00			#VALUE!	-1.28E+00	1.26E+00
Data from Run 8 - 7/15/93													
raw	0.00	NA	NA	0.00		#VALUE!	1.30E+04	1.30E+04	-	-	1.40E+04	< 1.00E+03	4.30E+04
ctrl	0.00					0.0	7.00E+04	7.00E+04	-	-	4.80E+04	< 1.00E+03	-
CL-5/1	5.00		0.00		?	0.0	< 2.00E+00	< 2.00E+00	-	-	9.00E+03	< 1.00E+01	-
CL-5/2	5.00		0.00			0.0	< 2.00E+00	< 2.00E+00	-	-	4.50E+01	< 1.00E+00	-
CL-5/3	5.00		0.00			0.0	< 2.00E+00	< 2.00E+00	-	-	1.40E+01	< 1.00E+00	-
CL-5/4	5.00		0.00			0.0	< 2.00E+00	< 2.00E+00	-	-	2.60E+01	< 1.00E+00	-
CL-10/1	10.00						2.00E+00	< 2.00E+00	-	-	2.50E+02	< 1.00E+01	
CL-10/2	10.00						< 2.00E+00	< 2.00E+00	-	-	8.00E+01	< 1.00E+00	
CL-10/3	10.00						< 2.00E+00	< 2.00E+00	-	-	1.20E+02	< 1.00E+00	
CL-10/4	10.00						< 2.00E+00	< 2.00E+00	-	-	< 1.00E+00	< 1.00E+00	
Log N/No													
raw	0.00	NA	#VALUE!	0.00		#VALUE!	-7.89E-01	-3.63E-01			7.66E-01	> -3.80E-01	-4.27E-01
ctrl	0.00	0.00	0.00	0.00		0.0	-5.80E-02	3.68E-01			1.30E+00	> -3.80E-01	
CL-5/1	5.00	0.00	0.00	0.00		0.0	> -4.60E+00	> -4.18E+00			5.74E-01	> -2.38E+00	
CL-5/2	5.00	0.00	0.00	0.00		0.0	> -4.60E+00	> -4.18E+00			-1.73E+00	> -3.38E+00	
CL-5/3	5.00	0.00	0.00	0.00		0.0	> -4.60E+00	> -4.18E+00			-2.23E+00	> -3.38E+00	
CL-5/4	5.00	0.00	0.00	0.00		0.0	> -4.60E+00	> -4.18E+00			-1.97E+00	> -3.38E+00	
CL-10/1	10.00	0.00	0.00	0.00		0.0							
CL-10/2	10.00	0.00	0.00	0.00		0.0							
CL-10/3	10.00	0.00	0.00	0.00		0.0							
CL-10/4	10.00	0.00	0.00	0.00		0.0	#NUM!	#NUM!			#NUM!	#NUM!	#NUM!

Cl Sample	Chlorine Dose, mg/L	Chlorine Free, mg/L	Chlorine Total, mg/L	Chlorine Comb., mg/L	Time min	CT min•mg/L	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/mL
Data from Run 9 - 8/4/93													
Raw		0.00	0 00				3.00E+03	3.00E+03			2 90E+04	9.50E+04	
Control		0.00	0.00	0.00	0	0.00	5.00E+04	2.40E+04			5 30E+04	1 20E+05	
Cl-5/1	5.00	3.60	3.92	0.32	1	3.60	< 2.00E+00	< 2 00E+00		< 1 00E+02	< 1 00E+02	< 1 00E+02	
Cl-5/2	5.00	3.34	3.66	0.32	5	16.70	< 2.00E+00	< 2.00E+00			2 00E+01	< 1 00E+01	
Cl-5/3	5.00	3.07	3.39	0.32	10	30.70	< 2.00E+00	< 2.00E+00			1 00E+01	< 1 00E+01	
Cl-5/4	5 00	2 97	3.29	0.32	15	44.55	< 2.00E+00	< 2.00E+00			6 70E+01	< 1 00E+00	
[illegible]	10 00	7 63	7 95	0 32	1	7.63	< 2.00E+00	< 2.00E+00			5 00E+01	< 1 00E+02	
[illegible]	10 00	7 63	7.95	0.32	5	38 15	< 2.00E+00	< 2.00E+00			1 00E+01	< 1 00E+01	
[illegible]	10 00	3 82	4 03	0.21	10	38.20	< 2.00E+00	< 2.00E+00			1.40E+01	< 1.00E+01	
Cl 10/4	10.00	3.82	4.03	0.21	15	57.30	< 2.00E+00	< 2 00E+00			1.80E+01	< 1 00E+00	
Log N/No													
Raw		0.00	0.00				0.00E+00	0.00E+00			0 00E+00	0.00E+00	
Control		0.00	0.00	0.00	0	0.00	1.22E+00	9.03E-01			2 62E-01	1 01E-01	
Cl-5/1		3.60	3.92	0.32	1	3.60	> -3.18E+00	> -3.16E+00		> -2.46E+00	> -2.98E+00		
Cl-5/2		3.34	3.66	0.32	5	16.70	> -3.18E+00	> -3.18E+00			-3 16E+00	> -3 98E+00	
Cl-5/3		3.07	3.39	0.32	10	30.70	> -3.18E+00	> -3.18E+00			-3.46E+00	> -3.98E+00	
Cl-5/4		2.97	3.29	0.32	15	44.55	> -3.18E+00	> -3.18E+00			-2 64E+00	> -4.98E+00	
Cl-10/1		7.63	7.95	0.32	1	7.63	> -3.18E+00	> -3.18E+00			-2 76E+00	> -2 98E+00	
Cl-10/2		7.63	7.95	0.32	5	38.15	> -3.18E+00	> -3.18E+00			-3 46E+00	> -3.98E+00	
Cl-10/3		3.62	4.03	0.21	10	38.20	> -3.18E+00	> -3.18E+00			-3.32E+00	> -3.98E+00	
Cl-10/4		3.82	4.03	0.21	15	57.30	> -3.18E+00	> -3.18E+00			-3 21E+00	> -4.98E+00	

Cl Sample	Chlorine Dose, mg/L	Chlorine Free, mg/L	Chlorine Total, mg/L	Chlorine Comb., mg/L	Time min	CT min*mg/L	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	Polio pfu/mL
Data from Run 10 - 8/24/93													
Raw		0.00	0.00				5.00E+03	2.30E+03			2.20E+04	2.60E+04	
Control		0.00	0.00	0.00	0	0.00	3.00E+04	2.40E+04			2.00E+04	4.00E+04	-
Cl-2/1		1.06	1.33	0.27	1	1.06	8.00E+00	4.00E+00			5.70E+03	< 1.00E+00	-
Cl-2/2		0.80	1.06	0.27	5	3.98	1.70E+01	< 2.00E+00			2.20E+03	< 1.00E+00	-
Cl-2/3		0.53	0.85	0.32	10	5.30	4.00E+00	4.00E+00			1.00E+03	< 1.00E+00	-
Cl-2/4		0.42	0.80	0.37	15	6.36	2.00E+00	< 2.00E+00			1.50E+03	< 1.00E+00	-
Cl-4/1		2.86	3.13	0.27	1	2.86	< 2.00E+00	< 2.00E+00			2.50E+01	< 1.00E+00	
Cl-4/2		2.39	2.70	0.32	5	11.93	4.00E+00	4.00E+00			3.10E+01	< 1.00E+00	
Cl-4/3		2.12	2.49	0.37	10	21.20	2.00E+00	2.00E+00			1.70E+01	< 1.00E+00	
Cl-4/4		2.01	2.39	0.37	15	30.21	2.00E+00	< 2.00E+00			1.50E+01	< 1.00E+00	
Log N/No													
Raw		0.00	0.00				0.00E+00	0.00E+00			0.00E+00	0.00E+00	
Control		0.00	0.00	0.00	0	0.00	7.78E-01	1.02E+00			-4.14E-02	1.87E-01	
Cl-2/1		1.06	1.33	0.27	1	1.06	-2.60E+00	-2.76E+00			-5.87E-01	> -4.41E+00	
Cl-2/2		0.80	1.06	0.27	5	3.98	-2.47E+00	> -3.06E+00			-1.00E+00	> -4.41E+00	
Cl-2/3		0.53	0.85	0.32	10	5.30	-3.10E+00	-2.76E+00			-1.34E+00	> -4.41E+00	
Cl-2/4		0.42	0.80	0.37	15	6.36	-3.40E+00	> -3.06E+00			-1.17E+00	> -4.41E+00	
Cl-4/1		2.86	3.13	0.27	1	2.86	> -3.40E+00	> -3.06E+00			-2.94E+00	> -4.41E+00	
Cl-4/2		2.39	2.70	0.32	5	11.93	-3.10E+00	-2.76E+00			-2.85E+00	> -4.41E+00	
Cl-4/3		2.12	2.49	0.37	10	21.20	-3.40E+00	-3.06E+00			-3.11E+00	> -4.41E+00	
Cl-4/4		2.01	2.39	0.37	15	30.21	-3.40E+00	> -3.06E+00			-3.17E+00	> -4.41E+00	

Sample ID#	UV dose mW•sec/cm2	Adj. UV Dose mW•sec/cm2	Total Colliorm MPN/100 mL	Fecal Colliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	eX174 pfu/mL	Polio pfu/mL
Run 1 - 10/6/92 (JML)										
raw	0		1.30E+05	5.00E+04	8.00E+03	2.70E+03	-	-	-	-
ctrl	0		7.00E+04	3.00E+04	3.00E+03	3.00E+03	-	-	-	-
1	30		< 20	< 20	2?	2?	-	-	-	-
2	50		< 20	< 20	< 2	< 2	-	-	-	-
4	90		< 20	< 20	< 2	< 2	-	-	-	-
3	100		< 20	2.00E+01	< 2	< 2	-	-	-	-
5	150		< 2	< 2	< 2	< 2	-	-	-	-
Log N/No										
raw	0		0.00	0.00	0.00	0.00				
ctrl	0		-0.27	-0.22	-0.43	0.05				
1	30		> -3.81	> -3.40	#VALUE!	#VALUE!				
2	50		> -3.81	> -3.40	> -3.60	> -3.13				
4	90		> -3.81	> -3.40	> -3.60	> -3.13				
3	100		> -3.81	-3.40	> -3.60	> -3.13				
5	150		> -4.81	> -4.40	> -3.60	> -3.13				
Run 2 - 11/3/92 (JML)										
	to be checked									
raw	0	0.00	2.30E+05	3.00E+04	1.30E+03 ?	2.00E+02	9.60E+04	4.00E+04	8.40E+04	-
ctrl	0	0.00	2.30E+05	1.10E+04	6.30E+02	8.30E+02	5.60E+04	6.70E+04	9.50E+04	-
1	16	13.32	9.00E+02	2.10E+02	8.00E+01	5.00E+01	2.90E+03	7.40E+03 <	5	-
2	20	16.38	1.10E+02	1.40E+01	2.00E+00	2.00E+00	1.20E+03	3.90E+03 <	10	-
3	32	31.09	8.00E+00	2.00E+00 <	2 <	2	1.20E+02	7.80E+02 <	10	-
4	40	40.73	1.10E+02 <	2 <	2 <	2	1.50E+02	2.30E+02 <	1	-
5	80	53.97	5.00E+01 <	2	NA	NA	1.90E+01	4.30E+01 <	1	-
Log N/No										
raw	0	0.00	0.00	0.00	0.00	> 0.00	0.00	0.00E+00	0.00	
ctrl	0	0.00	0.00	-0.44	-0.19	0.62	-0.23	2.24E-01	0.05	
1	16	13.32	-2.41	-2.15	-1.21	-0.60	-1.52	-7.33E-01 >	-4.23	
2	20	16.38	-3.32	-3.33	-2.81	-2.00	-1.90	-1.01E+00 >	-3.92	
3	32	31.09	-4.46	-4.18 >	-2.81 >	-2.00	-2.90	-1.71E+00 >	-3.92	
4	40	40.73	-3.32 >	-4.18 >	-2.81 >	-2.00	-2.61	-2.24E+00 >	-4.92	
5	80	53.97	-3.66 >	-4.18			-3.70	-2.97E+00 >	-4.92	
Run 3 - 1/4/93 (JML)										
raw	0	0.00	7.00E+04	7.00E+03	8.00E+02	1.70E+01	1.50E+05	2.10E+04	6.10E+04	-
ctrl	0	0.00	1.10E+05	3.00E+03 ?	2.40E+03 ?	2.20E+02	1.20E+05	1.90E+04	9.35E+04	-
1	17	16.05	6.00E+02	1.30E+02	5.00E+02	5.00E+02	1.00E+04	2.70E+03	3.55E+01	-
2	22	19.22	1.70E+01	4.00E+00	5.00E+01	5.00E+01	1.70E+03	1.80E+03 <	1.00E+00	-
3	34	25.10	< 2	< 2	2.00E+00	2.00E+00	7.30E+02	8.50E+02 <	1	-
4	44	42.49	< 2	< 2	< 2	< 2	4.60E+02	9.20E+01 <	1	-
5	51	41.84	< 2	< 2	< 2	< 2	4.40E+01	1.00E+02 <	1	-
Log N/No										
raw	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00E+00	0.00	
ctrl	0	0.00	0.20	-0.37 >	0.48 >	1.11	-0.10	-4.35E-02	0.19	
1	17	16.05	-1.94	-1.73	-0.20	1.47	-1.16	-8.91E-01	-3.24	
2	22	19.22	-3.61	-3.24	-1.20	0.47	-1.95	-1.07E+00 >	-4.79	
3	34	25.10	> -4.54	> -3.54	-2.60	-0.93	-2.31	-1.39E+00 >	-4.79	
4	44	42.49	> -4.54	> -3.54	> -2.60	> -0.93	-2.51	-2.36E+00 >	-4.79	
5	51	41.84	> -4.54	> -3.54	> -2.60	> -0.93	-3.53	-2.32E+00 >	-4.79	

Sample ID#	UV dose mW•sec/cm2	Adj. UV Dose mW•sec/cm2	Total Coliform MPN/100 mL	Fecal Coliform MPN/100 mL	Facal Streptococci MPN/100 mL	Enterococci MPN/100 mL	HPC cfu/mL	MS2 pfu/mL	øX174 pfu/mL	Polio pfu/mL
Run 4 - 1/11/93 (JML)										
raw	0	0.00	2.40E+04	8.00E+03	2.40E+03	2.40E+03	9.10E+04	2.30E+04	7.90E+04	-
ctrl	0	0.00	2.40E+05	3.00E+03	2.20E+03	2.20E+03 ?	9.80E+04	2.00E+04	8.90E+04	-
1	17	14.43	2.40E+02	8.00E+01	2.30E+01	2.30E+01	4.70E+03	3.70E+03	1.20E+01	-
2	22	15.10	3.00E+01	3.00E+01	3.00E+01	3.00E+01	4.00E+03	3.40E+03	2.00E+00	-
3	34	27.03	< 2	< 2	2.00E+00	2.00E+00	2.80E+02	7.50E+02	< 1	-
4	44	43.35	4.00E+00	< 2	2.00E+00	2.00E+00	1.10E+03	9.50E+01	< 1	-
5	51	45.43	< 2	< 2	< 2	< 2	1.70E+01	7.30E+01	< 1	-
Log N/No										
raw	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00E+00	0.00	
ctrl	0	0.00	1.00	-0.43	-0.04	-0.04	> 0.02	-8.07E-02	0.05	
1	17	14.43	-2.00	-2.00	-2.02	-2.02	-1.29	-7.94E-01	-3.82	
2	22	15.10	-2.90	-2.43	-1.90	-1.90	-1.36	-8.30E-01	-4.60	
3	34	27.03	> -4.08	> -3.60	-3.08	-3.08	-2.51	-1.49E+00	> -4.90	
4	44	43.35	-3.78	> -3.80	-3.08	-3.08	-1.92	-2.38E+00	> -4.90	
5	51	45.43	> -4.08	> -3.80	> -3.08	> -3.08	-3.73	-2.50E+00	> -4.90	
Run 5 - 1/19/93 (SAE)										
raw	0	0.00	8.00E+04	3.00E+04	2.40E+03	2.40E+03	1.15E+05	3.75E+04	7.20E+04	-
ctrl	0	0.00	2.40E+05	2.30E+04	3.00E+03	3.00E+03	8.35E+04	4.05E+05	8.35E+04	-
1	17	-0.61	8.00E+02	3.00E+02	8.00E+01	5.00E+01	3.25E+03	4.05E+04	5.00E+00	-
2	22	19.43	3.00E+02	5.00E+01	3.00E+01	3.00E+01	9.75E+02	3.20E+03	1.50E+00	-
3	34	28.54	1.30E+01	2.00E+00	< 2.00E+00	< 2.00E+00	8.85E+02	1.01E+03	< 1	-
4	44	29.07	2.30E+01	< 2	< 2.00E+00	< 2.00E+00	2.95E+03	9.45E+02	< 1	-
5	51	44.73	2.00E+00	2.00E+00	< 2.00E+00	< 2.00E+00	4.80E+01	1.30E+02	< 1	-
Log N/No										
raw	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00E+00	0.00	
ctrl	0	0.00	0.48	-0.12	0.10	0.10	-0.14	1.03E+00	-0.05	
1	17	-0.61	-2.00	-2.00	-1.48	-1.66	-1.55	3.34E-02	-4.18	
2	22	19.43	-2.43	-2.78	-1.90	-1.90	-2.07	-1.07E+00	-4.88	
3	34	28.54	-3.79	-4.18	> -3.08	> -3.08	-2.12	-1.57E+00	> -4.88	
4	44	29.07	-3.54	> -4.18	> -3.08	> -3.08	-1.59	-1.80E+00	> -4.88	
5	51	44.73	-4.60	-4.18	> -3.08	> -3.08	-3.38	-2.46E+00	> -4.88	
om Run 8 - 03/02/93										
raw	0	0.00	2.30E+04	2.30E+04	-	-	-	5.40E+04	-	3.50E+04
ctrl	0	0.00	5.00E+04	1.30E+04	-	-	-	5.20E+04	-	5.50E+04
1	17	15.08	1.70E+02	1.70E+02	-	-	-	8.00E+03	-	1.50E+03
2	22	13.72	2.30E+02	1.70E+02	-	-	-	9.50E+03	-	1.00E+03
3	34	28.84	2.30E+01	4.00E+00	-	-	-	1.40E+03	-	< 1.00E+02
4	44	42.77	1.30E+01	2.00E+00	-	-	-	2.40E+02	-	> 1.00E+00
5	51	49.76	1.30E+01	< 2	-	-	-	9.90E+01	-	> 1.00E+00
Log N/No										
raw	0	0.00	0.00	0.00				0.00E+00		0.00E+00
ctrl	0	0.00	0.34	-0.25				-1.64E-02		1.96E-01
1	17	15.08	-2.13	-2.13				-8.29E-01		-1.37E+00
2	22	13.72	-2.00	-2.13				-7.55E-01		-1.54E+00
3	34	28.84	-3.00	-3.76				-1.59E+00		> -2.54E+00
4	44	42.77	-3.25	-4.08				-2.35E+00		> -4.54E+00
5	51	49.76	-3.25	> -4.06				-2.74E+00		> -4.54E+00

Sample ID#	UV dose mW•sec/cm2	Adj. UV Dose mW•sec/cm2		Total Coliform MPN/100 mL		Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL		HPC cfu/mL		MS2 plu/mL	øX174 pfu/mL	Polio plu/mL
from Run 7 - 5/4/93														
raw	0	0.00	<	2.00E+00	<	2.00E+00	-	-		-		4.00E+04	-	1.60E+03
ctrl	0	0.00		2.30E+03		3.00E+03	-	-		-		3.00E+04	-	1.30E+04
1	17	14.85		2.30E+01	<	2.00E+00	-	-		-		6.10E+03	-	4.40E+03
2	22	13.11		3.00E+01		3.00E+01	-	-		-		7.60E+03	-	4.80E+03
4	34	29.96	<	2.00E+00	<	2.00E+00	-	-		-		9.00E+02	-	4.60E+01
3	44	26.47	<	2.00E+00	<	2.00E+00	-	-		-		1.40E+03	-	6.20E+01
5	51	61.78	<	2.00E+00	<	2.00E+00	-	-		-		1.60E+01	-	2.80E+01
Log N/No														
raw	0	0.00	>	-4.06E+00	>	-4.06E+00						0.00E+00		0.00E+00
ctrl	0	0.00		-1.00E+00		-6.85E-01						-1.25E-01		9.10E-01
1	17	14.85		-3.00E+00	>	-4.06E+00						-8.17E-01		4.39E-01
2	22	13.11		-2.88E+00		-2.88E+00						-7.21E-01		4.77E-01
4	34	29.96	>	-4.06E+00	>	-4.06E+00						-1.65E+00		-1.54E+00
3	44	26.47	>	-4.06E+00	>	-4.06E+00						-1.46E+00		-1.41E+00
5	51	61.78	>	-4.06E+00	>	-4.06E+00						-3.40E+00		-1.76E+00
'om Run 8 - 7/15/93														
Raw	0	0.00		1.30E+04		1.30E+04				1.40E+04	<	1.00E+03		4.30E+04
Control	0	0.00		1.70E+04		2.70E+03				1.60E+04	<	1.00E+03		7.30E+04
UV-1	17	23.86	<	2.00E+00	<	2.00E+00				1.20E+02		5.00E+01		2.30E+03
UV-2	22	30.89	<	2.00E+00	<	2.00E+00				1.30E+02		2.00E+01		1.60E+03
UV-3	34	54.55	<	2.00E+00	<	2.00E+00				2.00E+01	<	1.00E+00		1.30E+02
UV-4	44	54.55	<	2.00E+00	<	2.00E+00				1.50E+00	<	1.00E+00		3.30E+01
UV-5	51	54.55	<	2.00E+00	<	2.00E+00			<	1.00E+00		1.00E+00		0.00E+00
Log N/No														
Raw	0	0.00		0.00E+00		0.00E+00				0.00E+00	>	0.00E+00		0.00E+00
Control	0	0.00		1.17E-01		-6.83E-01				5.80E-02	>	0.00E+00		2.30E-01
UV-1	17	23.86	>	-3.81E+00	>	-3.81E+00				-2.07E+00		-1.30E+00		-1.27E+00
UV-2	22	30.89	>	-3.81E+00	>	-3.81E+00				-2.03E+00		-1.70E+00		-1.43E+00
UV-3	34	54.55	>	-3.81E+00	>	-3.81E+00				-2.85E+00	>	-3.00E+00		-2.52E+00
UV-4	44	54.55	>	-3.81E+00	>	-3.81E+00				-3.97E+00	>	-3.00E+00		-3.11E+00
UV-5	51	54.55	>	-3.81E+00	>	-3.81E+00			>	-4.15E+00		-3.00E+00		#NUM!

Sample ID#	UV dose mW•sec/cm2	Adj. UV Dose mW•sec/cm2		Total Coliform MPN/100 mL		Fecal Coliform MPN/100 mL	Fecal Streptococci MPN/100 mL	Enterococci MPN/100 mL		HPC cfu/mL	MS2 pfu/mL	øX174 pfu/mL	Polio pfu/mL
rom Run 9 - 8/4/93													
Raw	0	0.00		3.00E+03		3.00E+03	-	-		2.90E+04	9.50E+04		1.40E+04
Control	0	0.00		3.00E+03		2.30E+03	-	-		2.50E+04	1.00E+05		1.10E+05
UV-1	17	18.81		4.00E+00		4.00E+00	-	-		9.80E+02	9.00E+03		2.40E+03
UV-2	22	23.41		4.00E+00		4.00E+00	-	-		4.70E+02	4.90E+03		9.90E+01
UV-3	34	21.81	<	2.00E+00	<	2.00E+00	-	-	<	1.00E+01	6.00E+03		4.70E+00
UV-4	44	62.43	<	2.00E+00	<	2.00E+00	-	-		1.50E+00	3.50E+01		2.70E+00
UV-5	51	47.91	<	2.00E+00	<	2.00E+00	-	-		5.50E+00	2.20E+02		2.30E+00
Log N/No													
Raw	0	0.00		0.00E+00		0.00E+00				0.00E+00	0.00E+00		0.00E+00
Control	0	0.00		0.00E+00		-1.15E-01				-6.45E-02	2.23E-02		8.95E-01
UV-1	17	18.81		-2.88E+00		-2.88E+00				-1.48E+00	-1.02E+00		-7.86E-01
UV-2	22	23.41		-2.88E+00		-2.88E+00				-1.79E+00	-1.29E+00		-2.15E+00
UV-3	34	21.81	>	-3.18E+00	>	-3.18E+00			>	-3.46E+00	-1.20E+00		-3.47E+00
UV-4	44	62.43	>	-3.18E+00	>	-3.18E+00				-4.29E+00	-3.43E+00		-3.71E+00
UV-5	51	47.91	>	-3.18E+00	>	-3.18E+00				-3.72E+00	-2.64E+00		-3.76E+00
om Run 10 - 8/24/93													
Raw	0	0.00		5.00E+03		2.30E+03	-	-		2.20E+04	2.60E+04		3.00E+05
Control	0	0.00		1.30E+03		4.00E+02	-	-		1.60E+04	4.70E+04		2.20E+05
UV-1	17	14.59	<	2.00E+00	<	2.00E+00	-	-		6.90E+02	4.10E+03		3.10E+03
UV-2	22	21.09		2.00E+00		2.00E+00	-	-		2.10E+03	1.80E+03		2.00E+03
UV-3	34	31.20	<	2.00E+00	<	2.00E+00	-	-		1.60E+02	5.00E+02		3.30E+01
UV-4	44	43.16	<	2.00E+00	<	2.00E+00	-	-		2.50E+00	1.10E+02		1.60E+01
UV-5	51	55.18	<	2.00E+00	<	2.00E+00	-	-		1.50E+02	2.40E+01		3.30E+00
Log N/No													
Raw	0	0.00		0.00E+00		0.00E+00				0.00E+00	0.00E+00		0.00E+00
Control	0	0.00		-5.85E-01		-7.60E-01				-1.38E-01	2.57E-01		-1.35E-01
UV-1	17	14.59	>	-3.40E+00	>	-3.06E+00				-1.50E+00	-8.02E-01		-1.98E+00
UV-2	22	21.09		-3.40E+00		-3.06E+00				-1.02E+00	-1.16E+00		-2.16E+00
UV-3	34	31.20	>	-3.40E+00	>	-3.06E+00				-2.14E+00	-1.72E+00		-3.98E+00
UV-4	44	43.16	>	-3.40E+00	>	-3.06E+00				-3.94E+00	-2.37E+00		-4.27E+00
UV-5	51	55.18	>	-3.40E+00	>	-3.06E+00				-2.17E+00	-3.03E+00		-4.96E+00

Parameters	Units Testing	10/6/92 Bench	11/3/92 Bench	1/4/93 Bench	1/11/93 Bench	1/19/93 Bench	2/10/93 Full	2/25/93 Full	3/2/93 Bench	3/11/93 Full	3/24/93 Full	4/28/93 Full
Inorganic Analyses												
Temperature*	°C	28.0	25.5	19.0	19.5	19.0	19.5	19.0	20.0	20.0	22.0	-
pH		7.6	7.8	7.6	7.7	7.9	7.5	7.8	7.8	7.7	7.8	7.7
Alkalinity	mg/L		110	135	140	130	135	165	165	180	195	200
Turbidity	ntu	0.6	0.6	0.4	0.5	0.9	0.6	0.6	0.5	0.5	0.6	0.5
Particle Density (1-120 µm)	#/mL	5,300	3,100	2,700	1,600	4,100	2,800	3,209	4,840	3,209	6,170	2,357
TSS	mg/L	1.5	< 4.0	< 4.0	< 4.0	< 4.0	4.0	< 4.0	7.0	< 4.0	< 4.0	< 4.0 <
TDS	mg/L	400	580	850	790	700	720	840	820	960	910	980
Sodium	mg/L		150	135	165	115	125	185	200	160	185	175
Chloride	mg/L		125	150	160	130	150	170	180	180	180	170
Sulfate	mg/L		125	260	230	190	200	270	220	270	280	280
Calcium	mg/L		32	67	63	63	61	74	72	81	81	86
Nitrate-N	mg/L		13	13	12	13	14	14	13	12	9.8	11
Potassium	mg/L		11	13	10	6.3	7.1	9.3	10	9.7	12	11
Magnesium	mg/L		8	28	26	22	24	29	27	33	32	32
Iron	mg/L	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1 <
Organic Analyses												
TOC	mg/L	4.8	4.8	5.8	6.5	6.2	5.0	5.3	6.5	6.6	6.6	5.7
UV-254		0.129	0.129	0.121	0.141	0.142	0.144	0.131	0.134	0.144	0.144	0.126
UV-254 Transmittance	%	74.0	74.5	75.7	72.3	71.6	71.8	74.1	73.5	71.8	71.9	74.8
2-hr Chlorine Demand, mg/L												
Chlorine Dose, mg/L												
0.5			0.4		> 0.5	> 0.5						
1.0		> 1.0		> 1.0	> 1.0	> 1.0						
1.5			1.3		> 1.5	> 1.5						
2.0				2.0	> 2.0	> 2.0						
2.5			2.2									
3.0		2.5		2.6								
4.0				3.0	3.0	2.8						
5.0		3.1		3.1								
5.1			3.9									
7.6			4.8									
9.7						4.1						
10.0		3.2										
Bacterial Analyses (Indigeneous Organisms)												
HPC	cfu/mL		9.6 E+04	1.5 E+05	9.1 E+04	1.2 E+05	5.9 E+04	1.1 E+05	NA	Contamination	3.7 E+04	2.5 E+04
Total Coliform	MPN/100 mL	1.3 E+05	2.3 E+05	7.0 E+04	2.4 E+04	8.0 E+04	1.8 E+05	1.1 E+05	2.4 E+04	9.5 E+04	1.1 E+05	5.3 E+04
Fecal Coliform	MPN/100 mL	5.0 E+04	3.0 E+04	7.0 E+03	8.0 E+03	3.0 E+04	8.0 E+04	5.0 E+04	2.4 E+04	1.4 E+04	2.0 E+04	2.8 E+04
Fecal Streptococci	MPN/100 mL	8.0 E+03	1.3 E+03	8.0 E+02	2.4 E+03	2.4 E+03	6.0 E+03	9.0 E+03	NA	1.9 E+03	5.4 E+03	1.6 E+03
Enterococci	MPN/100 mL	2.7 E+03	2.0 E+02	1.7 E+02	2.4 E+03	2.4 E+03	3.8 E+03	3.0 E+03	NA	9.8 E+02	1.5 E+03	6.5 E+02
MS2	/mL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Polio	pfu/100L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA= Not Applicable
= not available
* On site analyses
< indicates less than minimum reporting level

Parameters	Units Testing	5/4/93 Bench	5/13/93 Full	5/19/93 Full	5/26/93 Full	6/2/93 Full	6/9/93 Full	6/16/93 Full	6/23/93 Full	6/29/93 Full	7/7/93 Full	7/14/93 Full/Bench	7/21/93 Full
Inorganic Analyses													
Temperature*	°C	23.5	24.0	25.0	25.0	25.0	25.0	26.5	26.5	27.0	27.0	27.0	26.5
pH		7.8	7.8	7.7	7.8	7.8	7.8	7.8	7.8	7.8	7.9	7.8	7.9
Alkalinity	mg/L	185	180	175	180	175	175	175	185	185	195	185	180
Turbidity	ntu	0.4	0.4	0.5	0.5	0.6	0.5	0.6	0.5	0.5	0.38	0.5	0.35
Particle Density (1-120 µm)	#/mL	1,770	2,275	2,463	2,600	3,510	2,341	1,926	2,317	3,406	1,283	1,527	2,433
TSS	mg/L	< 4.0	< 4.0	4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0
TDS	mg/L	920	870	840	870	850	840	850	890	860	890	890	880
Sodium	mg/L	175	180	165	175	185	175	170	175	165	170	175	190
Chloride	mg/L	170	170	175	160	170	160	160	180	165	170	165	165
Sulfate	mg/L	270	240	240	250	250	240	230	285	245	290	285	285
Calcium	mg/L	85	79	79	80	76	74	76	79	77	84	86	83
Nitrate-N	mg/L	10	10	9.7	10	9	9	8.9	9.7	6.6	5	6.6	7.7
Potassium	mg/L	10	10	11	9.7	11	11	11	11	11	12	11	10
Magnesium	mg/L	31	28	26	28	27	26	27	28	27	30	30	29
Iron	mg/L	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Organic Analyses													
TOC	mg/L	5.2	5.5	5.4	5.2	5.2	5.1	4.7	4.8	4.9	4.8	4.6	4.5
UV-254		0.123	0.118	0.116	0.112	0.128	0.106	0.115	0.113	0.11	0.105	0.104	0.101
UV-254 Transmittance	%	75.9	76.3	76.6	77.2	74.6	78.3	76.8	77.1	77.6	78.6	78.8	79.4
2-hr Chlorine Demand, mg/L													
Chlorine Dose, mg/L													
0.5													
1.0													
1.5													
2.0													
2.5													
3.0													
4.0													
5.0													
5.1													
7.6													
9.7													
10.0		2.3											
Bacterial Analyses (Indigeneous Organisms)													
HPC	cfu/mL	NA	8.8 E+04	4.8 E+04	8.1 E+04	1.5 E+05	NA	NA	NA	3.8 E+04	4.1 E+04	6.0 E+03	2.3 E+04
Total Coliform	MPN/100 mL	NA	1.3 E+05	3.7 E+04	9.0 E+04	1.8 E+05	6.0 E+04	8.0 E+04	2.7 E+04	5.0 E+04	2.7 E+04	2.4 E+04	5.5 E+04
Fecal Coliform	MPN/100 mL	NA	5.5 E+04	2.3 E+04	1.7 E+04	1.1 E+05	3.0 E+04	1.3 E+05	2.3 E+04	3.7 E+04	2.7 E+04	1.7 E+04	2.7 E+01
Fecal Streptococci	MPN/100 mL	NA	3.2 E+03	1.5 E+03	3.7 E+03	2.9 E+03	1.3 E+03	6.0 E+03	6.9 E+02	2.4 E+03	9.5 E+02	4.0 E+02	2.7 E+01
Enterococci	MPN/100 mL	NA	2.6 E+03	9.0 E+02	2.3 E+03	2.6 E+03	6.5 E+02	4.7 E+03	4.4 E+02	2.7 E+03	8.0 E+02	3.1 E+02	2.7 E+01
MS2	/mL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Polio	pfu/100L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA= Not Applicable
= not available
* On site analyses
< Indicates less than minimum reporting level

Parameters	Units Testing	7/27/93 Full	8/3/93 Full/Bench	9/14/93 Full	9/23/93 Full	9/29/93 Full
Inorganic Analyses						
Temperature*	°C	27.0	27.5	27.0	26.0	27.0
pH		7.8	7.9	7.8	7.7	7.2
Alkalinity	mg/L	180	180	170	170	175
Turbidity	ntu	0.52	0.75	0.69	0.29	1.24
Particle Density (1-120 µm)	#/mL	2,351	2,515	2,055	746	1,592
TSS	mg/L	< 4.0	< 4.0	< 4.0	< 10.0	< 10.0
TDS	mg/L	890	890	790	740	740
Sodium	mg/L	170	175	165	155	130
Chloride	mg/L	160	150	150	150	290
Sulfate	mg/L	285	270	220	175	355
Calcium	mg/L	83	83	71	69	66
Nitrate-N	mg/L	6.9	6.1	7.7	10	18
Potassium	mg/L	11	11	13	14	14
Magnesium	mg/L	30	29	24	22	23
Iron	mg/L	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Organic Analyses						
TOC	mg/L	4.8	4.8	5.3	5.7	6.2
UV-254		0.1	0.105	0.112	0.112	0.126
UV-254 Transmittance	%	79.6	78.7	77.4	77.4	74.9
2-hr Chlorine Demand, mg/L						
Chlorine Dose, mg/L						
0.5						
1.0						
1.5						
2.0						
2.5						
3.0						
4.0						
5.0						
5.1						
7.6						
9.7						
10.0						
Bacterial Analyses (Indigeneous Organisms)						
HPC	cfu/mL	2.3 E+04	4.0 E+04	4.5 E+04	8.5 E+03	2.0 E+04
Total Coliform	MPN/100 mL	1.9 E+04	1.5 E+05	7.0 E+04	1.3 E+04	2.2 E+04
Fecal Coliform	MPN/100 mL	9.0 E+03	1.6 E+05	3.5 E+04	5.3 E+03	1.2 E+04
Fecal Streptococci	MPN/100 mL	5.7 E+02	1.6 E+03	1.3 E+03	1.9 E+01	2.4 E+02
Enterococci	MPN/100 mL	3.2 E+02	1.6 E+03	2.2 E+02	9.0 E+00	1.0 E+02
MS2	/mL	NA	NA	NA	NA	NA
Polio	pfu/100L	NA	NA	NA	NA	NA

NA= Not Applicable
= not available
* On site analyses
< Indicates less than minimum reporting level

Tracer Feed Started at t=0			Tracer Feed Shut off at t=0									
Time (min)	Conductance (µs/cm)		Time (min)	Conductance (µs/cm)	Normalized Conductance	Slope	(-)Slope	Sum of (-)dC/dt avg.*dt	Percent of Tracer Past	(-dC/dt)*dti	(-dC/dt)*ti*dti	(-dC/dt)*ti*ti*dti
0	1389		0	2310	1.00	0.00	0.00	0.00	0.00	0.00	0	0
6	1390		6	2310	1.00	0.00	0.00	0.00	0.00	0.00	0	0
8	1390		8	2310	1.00	0.00	0.00	0.00	0.00	0.00	0	0
10	1390		10	2310	1.00	0.00	0.00	-2.50	0.00	0.00	0	0
12	1390		12	2310	1.00	2.50	-2.50	-2.50	0.00	-5.00	-60	-720
14	1390		14	2320	1.01	-2.50	2.50	5.00	0.00	5.00	70	980
16	1390		16	2300	0.99	-5.00	5.00	12.50	0.01	10.00	160	2560
18	1390		18	2300	0.99	-2.50	2.50	15.00	0.01	5.00	90	1620
20	1390		20	2290	0.98	0.00	0.00	12.50	0.01	0.00	0	0
22	1390		22	2300	0.99	2.50	-2.50	12.50	0.01	-5.00	-110	-2420
24	1390		24	2300	0.99	-2.50	2.50	15.00	0.01	5.00	120	2880
26	1390		26	2290	0.98	0.00	0.00	12.50	0.01	0.00	0	0
28	1390		28	2300	0.99	2.50	-2.50	5.00	0.00	-5.00	-140	-3920
30	1390		30	2300	0.99	5.00	-5.00	-5.00	0.00	-10.00	-300	-9000
32	1390		32	2320	1.01	5.00	-5.00	-12.50	-0.01	-10.00	-320	-10240
34	1391		34	2320	1.01	2.50	-2.50	-15.00	-0.01	-5.00	-170	-5780
36	1390		36	2330	1.02	0.00	0.00	-12.50	-0.01	0.00	0	0
38	1391		38	2320	1.01	-2.50	2.50	-7.50	-0.01	5.00	190	7220
40	1391		40	2320	1.01	-2.50	2.50	-2.50	0.00	5.00	200	8000
42	1391		42	2310	1.00	-2.50	2.50	2.50	0.00	5.00	210	8820
44	1397		44	2310	1.00	-2.50	2.50	15.00	0.01	5.00	220	9680
46	1410		46	2300	0.99	-10.00	10.00	47.50	0.04	20.00	920	42320
48	1420		48	2270	0.96	-22.50	22.50	115.00	0.11	45.00	2160	103680
50	1446		50	2210	0.89	-45.00	45.00	227.50	0.21	90.00	4500	225000
52	1500		52	2090	0.76	-67.50	67.50	338.00	0.32	135.00	7020	365040
54	1572		54	1940	0.60	-43.00	43.00	646.75	0.60	86.00	4644	250776
56	1650		56									
58	1700		58									
60	1821		60									
62	1872		62									
64	1898		64	1830	0.48	-18.75	18.75	686.00	0.64	187.50	12000	768000
66	1990		66	1777	0.42	-20.50	20.50	726.25	0.68	41.00	2706	178596
68			68	1748	0.39	-19.75	19.75	761.00	0.71	39.50	2686	182648
70			70	1698	0.34	-15.00	15.00	790.25	0.74	30.00	2100	147000
72			72	1688	0.32	-14.25	14.25	818.25	0.76	28.50	2052	147744
74	2080		74	1641	0.27	-13.75	13.75	833.50	0.78	27.50	2035	150590
76	2110		76	1633	0.26	-1.50	1.50	841.25	0.78	3.00	228	17328
78	2130		78	1635	0.27	-6.25	6.25	858.75	0.80	12.50	975	76050
80	2150		80	1608	0.24	-11.25	11.25	871.25	0.81	22.50	1800	144000
82	2130		82	1590	0.22	-1.25	1.25	870.00	0.81	2.50	205	16810
84	2180		84	1603	0.23	2.50	-2.50	872.25	0.81	-5.00	-420	-35280
86	2200		86	1600	0.23	-4.75	4.75	883.00	0.82	9.50	817	70262
88	2220		88	1584	0.21	-6.00	8.00	896.50	0.84	12.00	1056	92928
90	2240		90	1576	0.20	-7.50	7.50	914.50	0.85	15.00	1350	121500

Tracer Feed Started at t=0			Tracer Feed Shut off at t=0										
Time (min)	Conductance (µs/cm)		Time (min)	Conductance (µs/cm)	Normalized Conductance	Slope	(-)Slope	Sum of (-)dC/dt avg.*dt	Percent of Tracer Past	(-dC/dt)*dti	(-dC/dt)*ti*dti	(-dC/dt)*ti*ti*dti
									Dispersion Num. =		0.0555	

Appendix B

MONTGOMERY WATSON

APPENDIX B

COST ESTIMATES

A final objective of the EVMWD UV Disinfection Study was to compare the net present value costs of a full-scale UV system at the Regional Plant to the costs of continuing chlorination with the addition of dechlorination capabilities. The assumptions used in the cost comparison are summarized in Table B-1. The cost comparison is based upon a 20 year period, a net interest cost of 4.00%, and an average annual plant flow of 4.00 mgd.

CAPITAL COSTS

Capital improvements needed for the existing chlorination system are summarized in Table B-2. The chlorine feed equipment would need new evaporators, and the existing chlorine storage and chlorinator rooms would require a scrubbing and ventilation system. The capital cost to add dechlorination to meet the new toxicity limit in the plant's NPDES permit is summarized in Table B-3. Dechlorination capital improvements would include the addition of feed equipment, a housing facility, a scrubber system, and piping the addition of dechlorination to meet the new toxicity limit in the Regional Plant NPDES permit. The operation and maintenance costs for the chlorine and sulfur dioxide systems are detailed in Table B-4. A summary of the capital costs to purchase and install the existing UV system and install an additional UV channel are summarized in Table B-5.

O&M COSTS

The operation and maintenance costs for the UV system to produce an average UV dose of 140 mW•sec/sq are detailed in Table B-6. This is based on a measured average UV transmittance value for the effluent of 75.8%, an average sleeve fouling factor of 80% and an average lamp age reduction factor of 80%. To compare the cost of UV and chlorination/dechlorination, the annual O&M costs have been brought back to present costs and presented as net present value annual costs.

COST COMPARISON

The estimated capital and annual O&M costs for UV and chlorination/dechlorination disinfection alternatives are summarized in Table B-7. Comparison of the total net present

value costs for UV and chlorination/dechlorination show the chlorination/dechlorination costs are approximately 8% higher than the UV costs. This difference in the costs is less then the accuracy of the estimates themselves indicating that the cost of the two disinfection processes are comparable. However, UV disinfection offers several advantageous which include elimination of the storage, handling, and transport of a hazardous chemical; reduction of disinfected effluent chronic toxicity; and significant reduction of trihalomethanes and aldehydes in the disinfected effluent.

TABLE B-1

COST COMPARISON ASSUMPTIONS

ASSUMPTIONS FOR COMPARISON

Financial Assumptions

Time of Comparison	20	year	
Net Interest Cost	4.00%		interest-inflation

Plant Assumptions

Average Annual Plant Flow	4.00	mgd

Chlorination/Dechlorination Assumptions

Chlorine Dose	20	mg/l
SO2 Dose	10	mg/l

UV Assumptions

Average Dose	140	mWsec/cm^2
Avg UV Transmittance	75.80%	
Avg Sleeve Fouling	80%	
Avg Lamp Age Reduction Factor	80%	
Lamp Life	8760	hours
Ballast Replacement Freq	60	months
Lamp Cleaning Freq	1	months
Cleaning Time Required	8	manhours

Cost Assumptions

Chlorine	400	$/ton
SO2	500	$/ton
Electricity	0.08	$/kWh
Lamp Cost	$45.00	/lamp
Ballast Cost	$85.00	/lamp
Manpower Costs	$40.00	/hr

TABLE B-2

CAPITAL IMPROVEMENTS NEEDED FOR THE EXISTING CHLORINATION SYSTEM

CHLORINE SYSTEM

Evaporators

Provide 2 evaporators

Cost = $25,000

HVAC Improvements

The ventilation ducts will be required for the existing chlorine storage and chlorinator rooms.

The existing building is approximately 800 square feet (for the storage and chlorinator rooms).

Estimate $10 per square foot for ventilation systems

Cost = $8,000

Scrubbing and Ventilations System

The scrubber system should contain at least two 1-ton cylinders.

A 1-ton scrubber was specified for $90,000 for California City.
Estimate that a 2-ton scrubber is 50% more expensive.
Add 30% for installation and sales tax.

Cost = $176,000

Chlorination System

Evaporators	25000
HVAC Improvements	8,000
Scrubbing System	176,000
Capital Cost =	$209,000

TABLE B-4

O&M COSTS FOR CHLORINATION/DECHLORINATION

Operational Costs

Chlorine Feed

Daily Flow	4.00	mgd
Average Dose	20	mg/l
Daily Demand	667.2	lb/day
Annual Demand	121.8	tons
Unit Cost	400	$/ton
Annual Cost	$48,706	/yr

SO2 Feed

Daily Flow	4.00	mgd
Average Dose	10	mg/l
Daily Demand	333.6	lb/day
Annual Demand	60.9	tons
Unit Cost	500	$/ton
Annual Cost	$30,441	/yr

Maintenance

Chlorine Storage Maintenance	8	hr/month
Chlorinator Maintenance	8	hr/month
SO2 Storage Maintenance	8	hr/month
Sulfonator Maintenance	8	hr/month
Scrubber System Maintenance	8	hr/month

Total Maintenance Hours	40	hr/month
Manpower Cost	$40.00	/hr
Annual Cost	$19,200	/yr

Summary

Cl2 Costs	$48,706 /yr
SO2 Costs	$30,441 /yr
Maintenance	$19,200 /yr
Total	$79,147 /yr

TABLE B-5

CAPITAL COSTS FOR A UV SYSTEM

UV DISINFECTION SYSTEM

Capital Costs

UV Pilot Facility (existing)

Trojan Equipment	$419,000	from records
Construction Cost	$159,500	from records
Total Construction	$578,500	
Engineering	57850	@ 10%
Admin	17355	@ 3%
Total Facility Cost	$653,705	

Additional UV Channel

Equipment Costs	$310,000	(new controls, existing sw gr)
Construction Cost	$31,000	@10%
Total Construction	$341,000	
Engineering	34100	@ 10%
Admin	10230	@ 3%
Total Facility Cost	$385,330	

Summary - Capital Costs

Existing	$653,705
Additional	$385,330
Total Capital Cost	$1039035

TABLE B-6

O&M COSTS FOR UV

Operational

Power

Avg UV Transmittance	75.80%	
Avg UV Intensity	11.20	mW/cm2
Fouling Correction	80%	
Age Correction	80%	
Net Avg Intensity	7.17	mW/cm2
Exposure Time	10.9	seconds/bank
Dose per Bank	78.13	mWsec/cm2 per bank
Dose Required	140	mWs/cm^2
Banks Required	2	
Lamps per Bank	120	Lamps
Watts per Lamp	65	Watts
Watts per Bank	7800	Watts
Total Watts	15600	Watts
	15.6	kW
Hours per Day	24	
Days per Year	365	
Hours per Year	8760	h/yr
Total Power Consumption	136,656	kWh/yr
Unit Power Cost	0.08	$/kWh
Total Power Cost	$10,932	/yr

Lamp Replacement

Number of Banks in Operation	2	banks
Lamps per Bank	120	lamps
Lamps in Operation	240	lamps
Hours per year	8760	hours
Total Lamp-Hrs/yr	2,102,400	lamp-hr/yr
Lamp Life	8760	hours
Lamps per Year	240	lamps
Cost per Lamp	$45.00	
Total Annual Lamp Cost	$10,800	/yr

TABLE B-6 Continued

O&M COSTS FOR UV

Ballast Replacement

Number of Ballasts	240
Cost per Ballast	$85.00 /lamp
Replacement Cost	20,400

Financial Formulas

P/F = 1/(1+i)^n
where
P/F = present/future value
i= annual interest rate
n= number of years

A/P = (i*(1+i)^n)/((1+i)^n-1)
where
A/P = annual/present value

i=	4.00%
n, for A/P Calcs=	20 years

Year	P/F	A/P	Initial Cost	Net Ann Cost
5	0.8219	0.074	20,400	1,234
10	0.6756	0.074	20,400	1,014
15	0.5553	0.074	20,400	833
			Total	3,081

Total Ballast Cost $3,081 /yr

Lamp Cleaning Cost

Cleaning Time	8 hours
Lamp Cleaning Freq	1 months
Cleanings per Year	12 cleanings
Time per Year	96 mahours
Manpower Cost	$40.00 /hour
Lamp Cleaning Cost	$3,840 /yr

General Maintenance

Hours per Month	8 hr/month
Manpower Cost	$40.00 /hr
Annual Cost =	$3,840 /yr

TABLE B-6 Continued

O&M COSTS FOR UV

Summary - Operational Costs

Power	$10,932 /yr
Lamp Replacement	$10,800 /yr
Ballast Replacement	$3,081 /yr
Cleaning	$3,840 /yr
General Maintenance	$3,840 /yr
Total Operational Costs	$32,494 /yr

TABLE B-7

COST COMPARISON OF UV AND CHLORINATION/DECHLORINATION

COMPARISON OF SYSTEMS

Cost will be compared in terms of net present value.
To use this, the annual costs will be brought back to present costs.

P/A =(((1+i)^n-1)/(i*(1+i)^n)
where
P/A = present/annual value
i= annual interest rate
n= number of years

i= 4.00%
n, for A/P Calcs= 20 years
P/A = 13.59

	Capital Cost	Annual Cost	NPV of Annual	Total NPV Cost
Chlor/Dechlor System	522,000	79,147	1,075,628	1,597,628
UV System	1,039,035	32,494	441,601	1,480,636

Appendix C

MONTGOMERY WATSON

UV Disinfection Guidelines for Wastewater Reclamation in California and UV Disinfection Research Needs Identification

A Report
Prepared by the

National Water Research Institute

September 1993

For the State of California
Department of Health Services
Sacramento, California

Preface

The guidelines presented in this report are intended to provide guidance to regulatory staffs of the State of California Regional Water Quality Control Boards and the Department of Health Services (DHS) reviewing applications for use of ultraviolet (UV) disinfection systems in wastewater reclamation and reuse applications. These guidelines have no binding regulatory effect unless promulgated by DHS as official regulations.

The guidelines for UV disinfection and the identification of research needs that are the subject of this report were prepared by an independent panel of experts convened by the National Water Research Institute and the California Department of Health Services. To aid the Independent Panel in the development of the guidance criteria for UV disinfection, an ad hoc committee comprised of members from the Department of Health Services, two Regional Water Quality Control Boards, Orange County Water District, and the Metropolitan Water District of Southern California prepared a first draft of the guidelines. The document presented by the ad hoc committee served as a point of departure for the Independent Panel in its deliberations and in the preparation of this final report.

The Members of the Independent Panel were:

Dr. George Tchobanoglous, CHAIRPERSON
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University of Pittsburgh

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The Members of the Ad Hoc Committee were:

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Mr. Mark Adelson
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Mr. Chet Anderson
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Orange County Water District

In addition to the members of the Independent Panel and the Ad Hoc Committees, valuable input on specific technical and design issues related to UV disinfection applications was provided by the following consultants.

Consultants to the Independent Panel were:

Dr. William Cairns
Trojan Technologies, Inc.

Mr. Richard Pearcey
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Mr. Fred Soroushian
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Infilco Degremont, Inc.

Dr. Elliott Whitby
Fischer & Porter, Ltd.

Contents

Part I

UV Disinfection Guidelines

SECTION 1

Introduction

The guidelines that follow were, as noted in the preface, prepared by a committee convened by the National Water Research Institute and the California Department of Health Services. These guidelines have no binding regulatory effect unless promulgated by the California Department of Health Services (DHS) as official regulations. The basis for the guidelines, the issue of non conforming systems, and the organization of this report are addressed below.

Basis for the Guidelines

Unless otherwise indicated, it is assumed that ultraviolet (UV) disinfection is proposed as an alternative disinfection method for meeting the California Wastewater Reclamation Criteria (Title 22, Division 4, Chapter 3, of the California Code of Regulations) for uses where an oxidized, coagulated, filtered, disinfected effluent is required. The guidelines presented in this report were developed on the basis of the demonstrated equivalency of UV disinfection to chlorine disinfection as used in wastewater reclamation treatment plants. Equivalency of UV disinfection to a conventional process used in wastewater reclamation and reuse must be demonstrated by the following criteria:

1. Filtered effluent turbidity equal to or less than 2 NTU, met with the same statistical frequency as required for chlorine disinfection.
2. Total coliform count equal to or less than 2.2/100 mL met with the same statistical frequency as required for disinfection with chlorine.
3. Virus inactivation efficiency equivalent to that achieved with chlorine disinfection [4-logs of inactivation (i.e., 99.99 percent reduction), based on poliovirus].

Further, these criteria are based on currently available UV technology using low pressure mercury vapor UV lamps with flow parallel to the lamps in non-pressurized channels. Because of limited experience with the most restrictive wastewater reclamation applications ($\leq$ 2.2 total coliform/100 mL), the guidelines should be considered as interim, subject to revision as experience is gained with the demonstrated technology, with variations of the demonstrated technology, and with newly evolving technology.

Nonconforming UV Systems

UV disinfection systems that do not conform to the requirements set forth in this report may be acceptable if it can be demonstrated, to the satisfaction of the California Department of Health Services, that they provide a degree of treatment and reliability at least equal to systems that have been shown to be acceptable to the regulatory agencies. Determination of equivalency may require studies directed at the inactivation of viruses or other microorganisms by the proposed UV system. Specific conditions that would require the determination of equivalency using a standard predetermined protocol would include, but not be limited to, the following:

1. When UV disinfection systems with different lamp orientation are proposed.
2. When a UV disinfection system is proposed with a different UV dose than that called for in the guidelines.
3. When medium and high energy UV lamps are proposed.

4. When a UV disinfection system is proposed for a wastewater reclamation application where the transmittance of the filtered effluent is below 55 percent.

Organization of Report

The guidelines are organized into the following sections.

- Dose and Reactor Design
- Reliability Design
- Monitoring and Alarm Design
- Required Field Testing Before Startup
- Compliance Monitoring
- Engineering Report

The first five topics deal specifically with the key elements involved in the design, operation, and monitoring of a UV disinfection system. These five topics must be addressed in the engineering report that is required when it is proposed to use UV disinfection in place of chlorine or related compounds. Pertinent references cited in this report may be found following the discussion of the Engineering Report (Section 7). Research priorities in UV disinfection are presented in a separate section following the guidelines. (See Part II)

SECTION 2

Dose and Reactor Design

Key elements of a UV disinfection system include the average UV dose delivered to the fluid and the design of the UV reactor. These subjects are addressed in the following paragraphs.

UV Dose

The UV dose is defined as the product of the average UV intensity, expressed in milliwatts per square centimeter (mW/cm^2), and the average exposure time of the fluid to be treated, expressed in seconds (s). UV dose is expressed in units of milliwatts seconds per square centimeter ($mW \cdot s/cm^2$). A UV disinfection system for the most restrictive reuse applications specified in the Wastewater Reclamation Criteria ($\leq$ 2.2 total coliform/100mL) should be designed to deliver, under worst operating conditions, a minimum UV design dose of 140 $mW \cdot s/cm^2$ at maximum week flow and 100 $mW \cdot s/cm^2$ at peak flow (maximum day). The minimum required design dose must be based on the following conditions:

1. UV lamp output = 70 % of nominal (new) UV lamp output.
2. Transmittance through quartz sleeves = 70 percent.
3. Minimum allowable wastewater transmittance = 55 percent . (If continuous transmittance data have been collected for a minimum period of six months including wet weather periods, a higher transmittance value may be allowed).
4. UV dose calculation method = point source summation.
5. UV dose is to be achieved with a minimum of three UV banks in series.

Rationale

Based on pilot testing of UV disinfection with filtered secondary effluent, it has been found that a UV dose varying from 100 to 120 $mW \cdot s/cm^2$ will achieve 4 logs (log $(N/N_o) = -4$) of inactivation of poliovirus (Chen 1992; CH2M-Hill 1992). To be equivalent to Wastewater Reclamation Criteria with chlorine disinfection, 4 logs of virus inactivation are required. The reported UV doses, in the cited studies, were calculated for a horizontal lamp configuration using a proprietary UV dose estimation model. When the UV dose is recomputed using the point source summation (PSS) method for computing the UV intensity, the corresponding UV dose values are approximately 120 to 140 $mW \cdot s/cm^2$.

Based on the test results cited above, the operational average UV dose should be equal to or greater than 140 $mW \cdot s/cm^2$. The recommended UV dose estimation procedure is based on restrictive worst-case conditions. This design procedure provides a common basis for all UV manufacturers on which to base their equipment requirements. In wastewater reclamation facilities where a constant flow is treated, the design UV dose corresponds to the operating UV dose (140 $mW \cdot s/cm^2$). In wastewater reclamation facilities where a variable flow is treated, the probability that the minimum fluid transmittance, the peak flow rate, lamp coating at its design limit, and lamps at the end of their useful life will all occur simultaneously, is highly unlikely. Should all of the design conditions occur simultaneously, the standby UV bank or channel (see Section 3) would be put into operation to maintain the operational average UV dose.

To standardize the computation of the average UV radiation (intensity) within the UV reactor, the EPA point source summation method (PSS) is to be used. In the new EPA UV disinfection model (UVDIS Version 3.1), currently under review, the UV intensity computation is based on the PSS method.

Reactor Design

UV disinfection contact chambers should be designed with inlet, channel approach, and outlet conditions that promote plug flow within the system. Inlets should be designed to allow for equal flow distribution among the UV channels. Channel approach conditions should allow sufficient distance to develop a uniform flow field upstream of the first bank of UV lamps in a system. The outlet condition should be such that hydraulic behavior within the last bank of lamps is not affected by the outlet fluid level control device. Good transverse (cross-sectional) mixing should also be promoted within the system. To ensure proper inlet and outlet flow conditions the following criteria are suggested:

1. Unobstructed approach channel length before first UV bank = 2 x (channel water depth) or 4 ft minimum.
2. Unobstructed downstream channel length following last bank of UV lamps before fluid level control device = 2 x (channel water depth) or 4 ft minimum.
3. Spacing between UV banks = minimum spacing required for maintenance and access.
4. To avoid the growth of algae containing biofilms, the upsteam and downstream portions of the UV reactor channel and the sections of the channel between the UV banks must be covered (light tight).

Rationale

Based on current theory, "turbulent plug flow" is considered to be conducive to good performance within a UV reactor. A properly designed inlet structure and approach channel will help to ensure that plug flow conditions are imposed on the first bank of lamps in a UV disinfection channel. Tests performed on horizontal lamp arrays indicate that the lamps are effective in promoting plug flow conditions. Therefore, hydraulic conditions are forced into a "plug flow like" condition by passing through UV lamp modules. A properly designed outlet structure will ensure that outlet conditions do not affect fluid behavior within the last UV array. Because the lamps themselves virtually guarantee plug flow behavior, favorable hydraulic conditions may be ensured in the entire reactor if inlet and outlet structures are designed properly.

SECTION 3

Reliability Design

Because the total coliform standards specified in the most restrictive Wastewater Reclamation Criteria (Title 22) are extremely stringent, special attention must be devoted to the reliability of any proposed UV disinfection system. The design of the UV system (e.g., number and configuration of UV banks) and the provision of standby power are of critical importance. Because of seismic activity within the state, seismic design is also an important design consideration.

UV System Design

Key elements of the UV system design include the minimum of 3 UV banks in series and the provision for UV system redundancy.

MINIMUM NUMBER OF UV BANKS

The UV disinfection system (channel) should be designed to deliver the minimum UV design dose (see Section 2), under worst case operating conditions, with a minimum of three UV banks in series.

UV SYSTEM REDUNDANCY

Redundancy (standby capacity) can be provided as follows.

1. Provide either one standby UV bank per channel or one or more standby channels, depending on the size of the installation. Where a standby UV bank is used, a minimum of four UV banks must be installed initially in each disinfection channel.
2. Provide automatic alternation of the standby bank or standby channel.

Rationale

Based on current experience with the most restrictive wastewater reclamation criteria, it appears that a minimum of three banks is necessary to minimize short circuiting and inadequate disinfection that could occur with fewer banks. For example, with a single bank of lamps in service, an individual lamp failure may result in organisms passing through the bank without receiving an adequate dose of UV. Because one bank at a time will need to be removed for cleaning and maintenance, there is a need for at least four bank locations to be provided in each channel. Any event (such as multiple lamp failure) or a decrease in filter effluent quality which reduces the effectiveness of an individual bank of lamps can be offset by activating the standby bank.

Backup Power

Backup power and power supply reliability should be provided as required in the Wastewater Reclamation Criteria. In addition, to assure a continuous supply of power to all facilities, should one of the power supply lines fail, a looped power distribution system should be provided. Another feature that could enhance the system reliability at minimal cost increase would be to divide the disinfection system components of the same type (i.e., banks) between two or more power distribution panel boards or switch boards.

Rationale
Because the UV disinfection system cannot operate without electrical power, backup power is essential to assure continuous disinfection, unless the reclamation plant has alternative reliability provisions or capabilities as outlined in the Wastewater Reclamation Criteria. Using multiple panel boards or switch boards would allow part of the system to remain on line, even if one of the power distribution panel boards or switch boards should fail.

Electrical Safety Design

All UV systems shall be provided with ground fault interrupt circuitry.

Rationale
Ground fault interrupt circuitry is required to minimize hazard to plant personnel in the event of a lamp break or other event that creates direct electrical contact with water.

Seismic Design

The UV system should be designed in accord with the seismic design requirements of Section 2312 of the Uniform Building Code for "special occupancy structures" in the appropriate seismic zone. These same seismic design standards shall apply to structures in which UV replacement lamps are stored on site.

Rationale
Seismic design considerations are particularly important for UV systems because of the fragile components (especially lamps and quartz sleeves) used in the systems. The seismic safety design of the UV disinfection system should be at least equivalent to the design of the reclamation facilities prior to disinfection. This provision will assure that whenever the plant is capable of producing effluent, the UV system will provide adequate disinfection at all times.

SECTION 4

Monitoring and Alarms

The ability to monitor operating parameters continuously is of fundamental importance in the operation of a UV disinfection system. The design of the alarm system is critical in maintaining the performance of the UV disinfection system.

Continuous Monitoring

Continuous monitoring should be provided for the following parameters:

WASTEWATER

1. Flow rate
2. Fluid transmittance
3. Turbidity
4. Liquid level in UV disinfection channels

UV DISINFECTION SYSTEM

1. Status of each UV bank, On/Off
2. Status of each UV lamp, On/Off
3. UV intensity measured by at least one probe per bank.
4. Lamp age in hours

Rationale

The parameters identified above are needed to determine the UV dose and to monitor the operation of the UV system. Flowrate and transmittance are needed to determine the average UV dose. Turbidity monitoring can be used to turn on an additional UV bank or a UV reactor in response to deteriorating filter effluent quality. The depth of water in the UV channels must be controlled carefully to prevent the depth of water above the highest UV lamps from exceeding a predetermined design maximum value, allowing organisms to be exposed to a lower than average UV intensity and to prevent lamps from being out of the flow and losing the effect of their UV light due to low water levels. The status of each UV bank and UV lamp is needed to provide on line monitoring of the operation of the UV system and to control the alarm system. UV intensity and lamp age are used to determine the average UV intensity.

Continuous Monitoring of UV Dose

The average UV dose delivered to each UV reactor is to be monitored continuously. The average UV intensity within the reactor is to be computed using the PSS method. Input data for the computation of UV intensity include: 1) fluid transmittance, 2) the degree of lamp fouling, and 3) average age of the UV lamps. The average UV dose is then computed by multiplying the average exposure time, determined from the flowrate, by the average UV intensity. The UV dose should be increased automatically to compensate for high turbidity readings or low UV dose, or both, by activating an additional bank or channel, depending on the method used to provide redundancy (see Section 3). The alarm system should be activated if the average UV dose falls below 140 $mW \cdot s/cm^2$ for more than three minutes.

Rationale

Continuous determination of UV dose is technologically feasible and is consistent with the current requirement for continuous chlorine residual monitoring. Use of the average UV intensity to calculate UV dose is a reasonable approach advocated by the U.S. EPA and the industry. The average UV intensity accounts for the UV light that an organism would be subjected to if traveling through the reactor under turbulent flow conditions.

Alarms

Both high-priority and low-priority alarms are required to operate a UV disinfection system effectively. Major alarms, if left unattended, may compromise the performance of the UV system. Minor alarms, if left unattended, will not compromise the performance of the UV system. The required major and minor alarms are as follows:

HIGH-PRIORITY (MAJOR) ALARMS

- Adjacent lamp failure — two or more adjacent lamps have failed.
- Multiple lamp failure — more than 5 percent of the lamps in a bank have failed.
- Low-Low UV intensity — when the lamp bank probe intensity drops below a field adjustable set point.
- Low-Low UV transmittance — when the influent wastewater UV transmittance drops below a field adjustable set point.
- High-high turbidity — when the influent wastewater turbidity exceeds a field adjustable set point.

Rationale

The UV dosage should be increased by activating the redundant channel or lamp banks in response to high-priority alarms (i.e., when the UV disinfection performance is being compromised).

LOW-PRIORITY (MINOR) ALARMS

- Individual lamp failure — location of the lamp to be indicated by bank, module and lamp sequence.
- Low UV intensity — when the lamp bank probe intensity drops below a field adjustable set point.
- Low UV transmittance — when the influent wastewater UV transmittance drops below a field adjustable set point.
- High turbidity — when the influent wastewater turbidity exceeds a field adjustable set point.
- High or low water levels in disinfection channel

Rationale

Low-priority alarms indicate that maintenance is required. For example, low or high water levels in the UV channel should cause a low-priority alarm, requiring the operator to investigate the problem. The operator may activate an additional UV channel during investigation or repair.

UV Alarm Records

The UV system should be designed to record automatically all high and low-priority alarm conditions.

SECTION 5

Field Testing Before Startup

In addition to the field testing of the UV electrical components, the following hydraulic tests should be conducted to verify the physical performance of the UV disinfection system.

Hydraulic Residence Time Testing

Tracer studies of the UV reactors should be conducted to define residence time distributions. Tracer studies should be conducted at the minimum anticipated flow and at 50, 75 and 100 percent of the peak design flow. Tests should be conducted with all of the UV banks and lamps in place. In large open channel systems where complete mixing of the tracer before entering the UV bank cannot be achieved, tracer should be injected at nine points uniformly distributed over the cross-sectional plane perpendicular to the direction of the fluid flow.

Hydraulic residence time testing may be waived for small treatment plants on the approval.the the Department of Health Services. Approval to waive onsite tracer testing should be based on objectively substantiated tracer testing on equivalent installations of a particular UV disinfection unit.

Rationale
The numerical relationships between the average exposure time and flow rates for a reactor can only be verified by a tracer study.

Water Level Verification

The downstream water level control system should be capable of maintaining the water level within a prescribed range.

Rationale
Verification of the variation of depth of flow in the UV channel is of critical importance in computing the average UV dose.

Compliance Monitoring

Compliance monitoring for UV disinfection systems will include both grab samples, a variety of continuous on-line measurements, and continuous monitoring of the average UV dose.

Grab Samples

Routine monitoring based on representative grab samples should include the following:

1. Total coliform bacteria, daily.
2. Suspended solids, daily

The samples for both coliform bacteria and suspended solids shall be collected daily at a time when wastewater characteristics are most demanding on the treatment facilities and disinfection facilities. Suspended solids may already be collected in connection with the effluent filtration system.

Rationale

The required sampling program for compliance is consistent with the existing sampling program set forth in the Wastewater Reclamation Criteria. The results of the suspended solids testing should ultimately be correlated to the corresponding turbidity readings.

Continuous Measurement

Routine UV disinfection system monitoring based on continuous on-line measurement should include:

WASTEWATER

1. Flow rate
2. Fluid transmittance
3. Turbidity
4. Liquid level in UV disinfection channels

The use of fluid transmittance measurements based on grab samples may be allowed for small treatment plants on the approval of the Department of Health Services.

UV DISINFECTION SYSTEM

1. UV intensity
2. Lamp age in hours

Rationale

Submission of data on the above parameters will serve to demonstrate that the UV disinfection system was operational continuously.

UV Dose

The operational average dose must at all times be at least 140 $mW \cdot s/cm^2$, based on continuous monitoring. The average UV dose is the product of the average UV intensity and the average exposure time of the fluid. The average UV intensity is determined using the point source summation (PSS) method. The average exposure time shall be determined from the residence time distribution curves as determined by field testing before startup.

Rationale

Continuous disinfection in conventional wastewater reclamation treatment processes is indicated by the presence of a specified disinfectant residual as coliform bacteria are measured infrequently. Because the concept of disinfectant residual is not applicable to UV, a different means of assuring that the minimum average UV dose is maintained is required. On-line continuous monitoring of the average UV dose, in conjunction with the other continuous parameter monitoring data, is to serve as a substitute for the measurement of residual in chlorine disinfection.

SECTION 7

Engineering Report

For existing and proposed wastewater reclamation facilities for which an engineering report has not been submitted, a complete engineering report, as outlined below, must be submitted prior to implementation of disinfection with a UV disinfection system.

For existing wastewater reclamation facilities for which an engineering report acceptable to the regulatory agencies has been submitted and for which UV disinfection is proposed for disinfection purposes, the following types of reports may be required:

1. A complete, updated engineering report may be required if, since submission of the original engineering report, changes or modifications have occurred in the production of reclaimed water (e.g., raw or treated water quality, treatment processes, plant reliability features, monitoring, or operation and maintenance procedures), reclaimed water transmission and distribution system, or reclaimed water use areas (e.g., type of reuse, use area controls, or use area design). The necessity to submit a complete, updated engineering report in lieu of an abbreviated report in which only the UV disinfection system is addressed will be at the discretion of the regulatory agencies.
2. An abbreviated engineering report in which only the UV disinfection system and attendant treatment and reliability features is addressed is acceptable only if the proposed modifications solely involve disinfection processes (e.g., replacing or enhancing existing disinfection facilities with UV disinfection facilities).

Elements of Engineering Report

Topics addressed in an engineering report should include, but not be limited to, the following:

PRODUCER

The producer is the public or private entity that will treat the wastewater used in the project. Where more than one agency is involved in the treatment, the responsibilities of each agency must be described.

PURVEYOR

The person, party, or agency responsible for the reclaimed wastewater distribution system.

RAW WASTEWATER

State the physical, chemical, and biological characteristics of the wastewater. Any unusual characteristics that may affect the UV disinfection system (e.g., variable transmittance) must be identified. State the proportion and type of industrial waste.

RECLAIMED WATER

State the treatment processes and quality of water that are required and will be provided for each reclaimed use.

TREATMENT PROCESSES

Provide a schematic diagram of the complete wastewater treatment flow diagram. State the existing or expected quality of the wastewater that will be subject to disinfection by UV radiation.

UV REACTOR DESIGN

Provide a schematic of the UV system. The schematic should be in sufficient detail to clearly indicate compliance with design and operational requirements specified in the Wastewater Reclamation Criteria (Title 22). As a minimum the following information should be provided:

1. Contact channel dimensions and number of channels.
2. Theoretical and mean residence time in each channel. Discuss the method of determining residence time.
3. Number and type of UV lamps, modules, and banks.
4. Water level relative to UV lamps.
5. Lamp arc length.
6. Lamp arrangement.
7. Minimum UV dose under worst case conditions. Include anticipated lamp output, UV transmittance through quartz sleeves, lowest anticipated UV transmittance in the wastewater, maximum flow, and minimum exposure time.
8. Number, location, and function of UV intensity and/or transmittance probes.

The UV system should be designed in accordance with the seismic design requirements of Section 2312 of the Uniform Building Code, Title 24, for "special occupancy structures" in the appropriate seismic zone (Zone 3 or Zone 4 in California).

RESIDENCE TIME DISTRIBUTION

Prior to the production of any reclaimed wastewater, the actual residence time distribution in the UV channel(s) must be determined. The protocol for determining the residence time distribution under various flow conditions should be described in the engineering report.

MONITORING

The report must describe a monitoring program that complies with the Wastewater Reclamation Criteria, and includes frequency and location of sampling. Where continuous analyses and recording equipment is used, the method and frequency of calibration must be stated.

1. Describe the monitoring system used to determine and record the UV dose, including equipment and procedures used to monitor and record flow, UV intensity, and UV transmittance.
2. Describe the method of monitoring water level in the contact channels.
3. Describe the method of monitoring lamp outages.
4. Describe the sampling location used to determine compliance with the microbiological requirements specified in the Wastewater Reclamation Criteria.

RELIABILITY

The UV system reliability features proposed to comply with Title 22 of the Wastewater Reclamation Criteria must be described in detail. The discussion of each reliability feature must state under what conditions it will be actuated. When alarms are used to indicate system failure, the report must state where the alarm will be received, how the location is staffed, and who will be notified. The report must state the hours the plant will be manned.

OPERATION AND MAINTENANCE

The engineering report must include an operations plan for system operation and maintenance. The operations plan should include a description of the control system, alarm functions, records, and reports. The plan should outline procedures and intervals for cleaning sleeves, frequency or criteria for replacing lamps, and frequency of calibration of monitoring equipment. The location, access, and quanitity of a backup supply of lamps and other critical components should be identified.

CONTINGENCY PLAN

The Wastewater Reclamation Criteria requires that the engineering report contain a contingency plan designed to prevent inadequately treated wastewater from being delivered to the user. As it relates to the UV system, the contingency plan must include:

1. A list of conditions that would require an immediate diversion to take place.
2. A description of the diversion procedures.
3. Designation of the diversion area.
4. A plan for the disposal or treatment of any inadequately treated effluent.
5. A plan for notifying the reclaimed water user, the regional board, the state and local health departments, and other agencies as appropriate, of any treatment failures that could result in the delivery of inadequately treated wastewater to the use area.

Nonconforming UV Systems

UV disinfection systems that do not conform to the requirements specified in the Wastewater Reclamation Criteria may be acceptable if it can be demonstrated to the satisfaction of the California Department of Health Services that they provide a degree of treatment and reliability equal to systems that have been shown to be acceptable to the regulatory agencies. Determination of equivalency may require studies directed at the inactivation of viruses or other microorganisms by the UV system. Engineering reports for nonconforming UV systems will not be approved by the regulatory agencies unless and until the California Department of Health Services has approved the nonconforming system as being capable of providing acceptable levels of treatment and reliability.

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Appendix D

MONTGOMERY WATSON

APPENDIX D

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